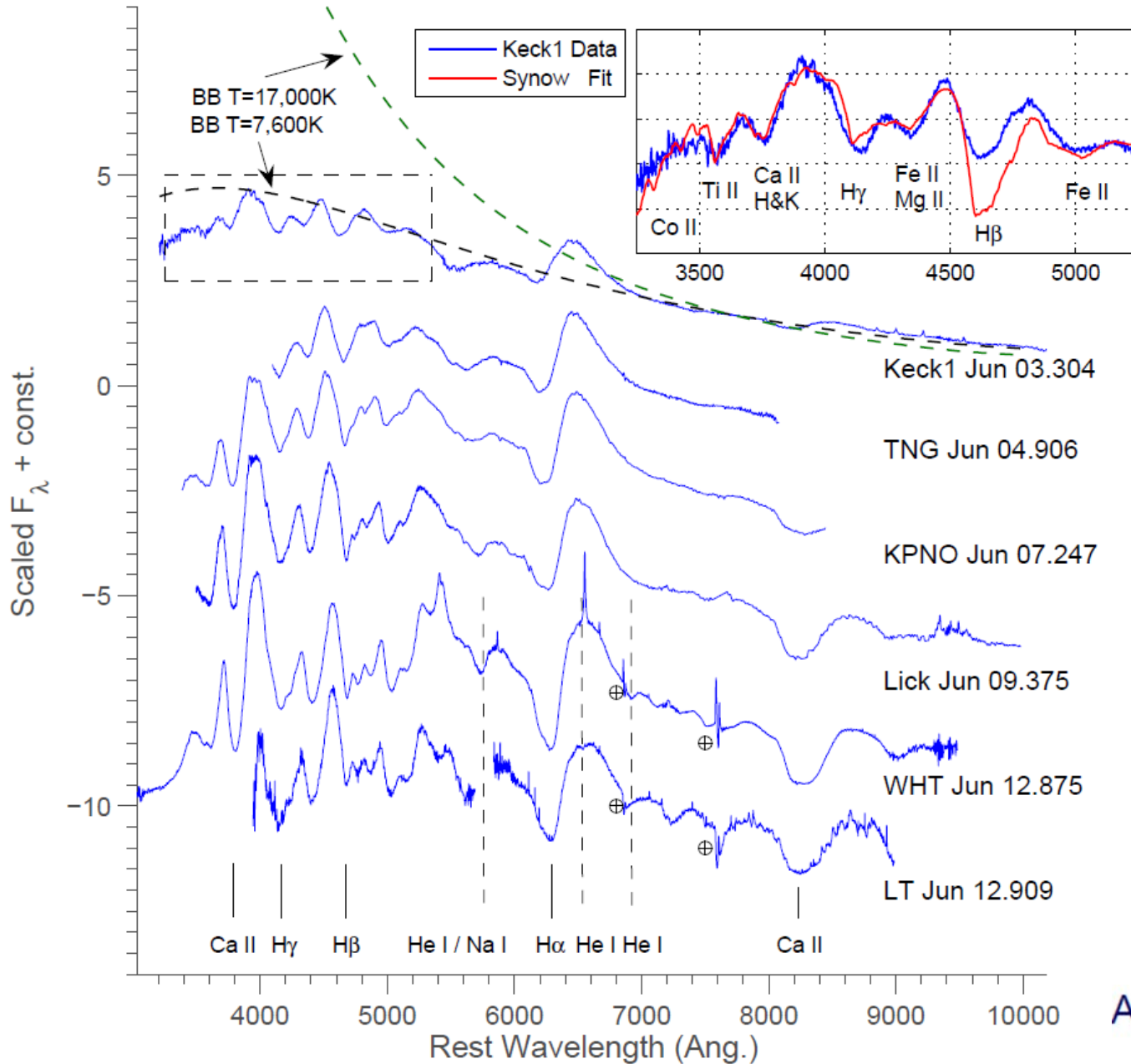


Type IIb SN 2011dh

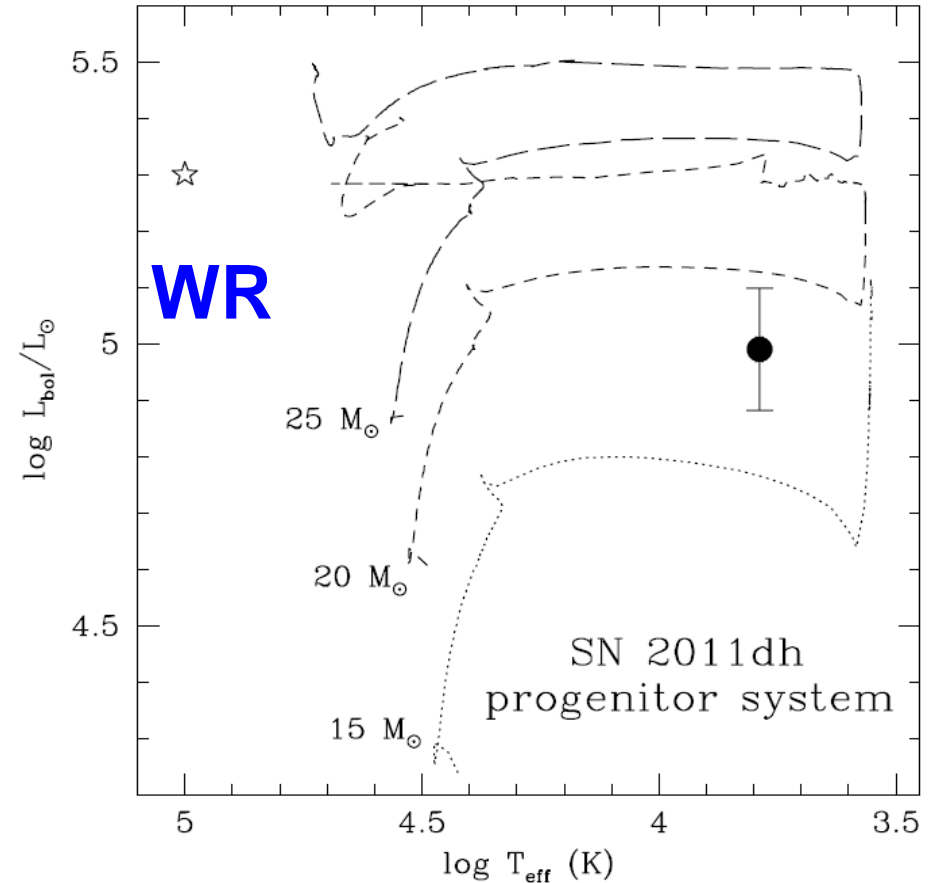
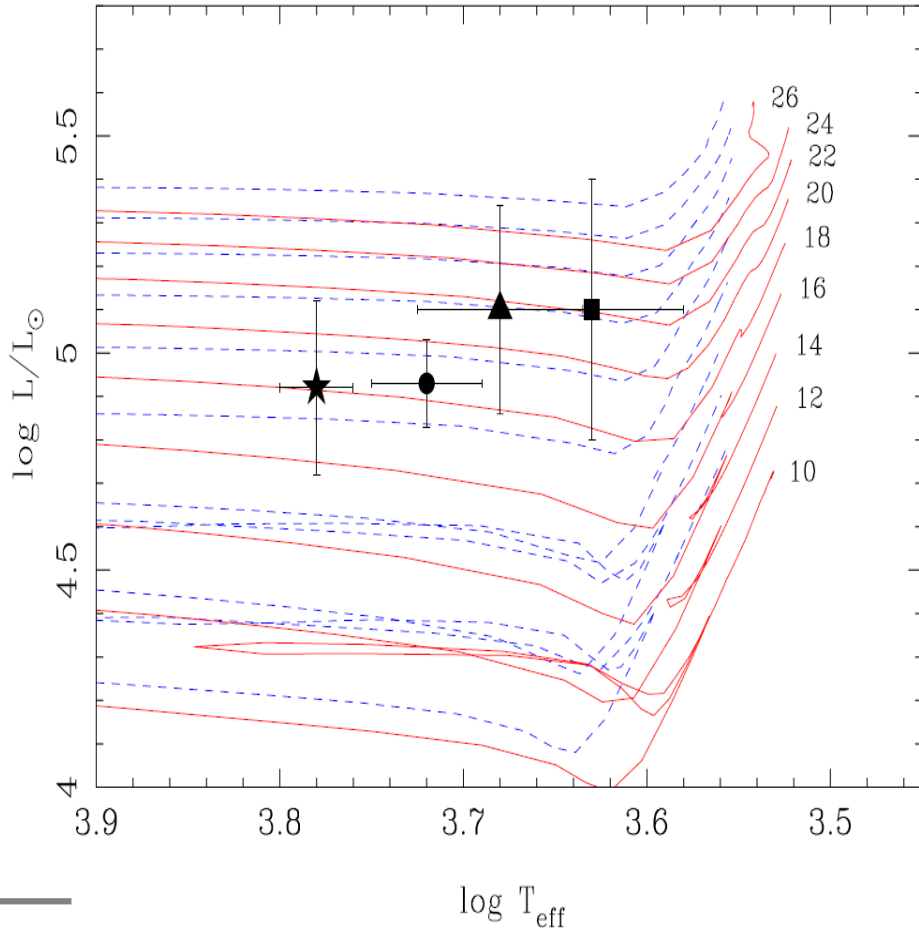


K. Nomoto (IPMU, U. Tokyo)

SN I Ib 2011dh



Yellow Supergiant ? Progenitor of Type IIb SN 2011dh in M51



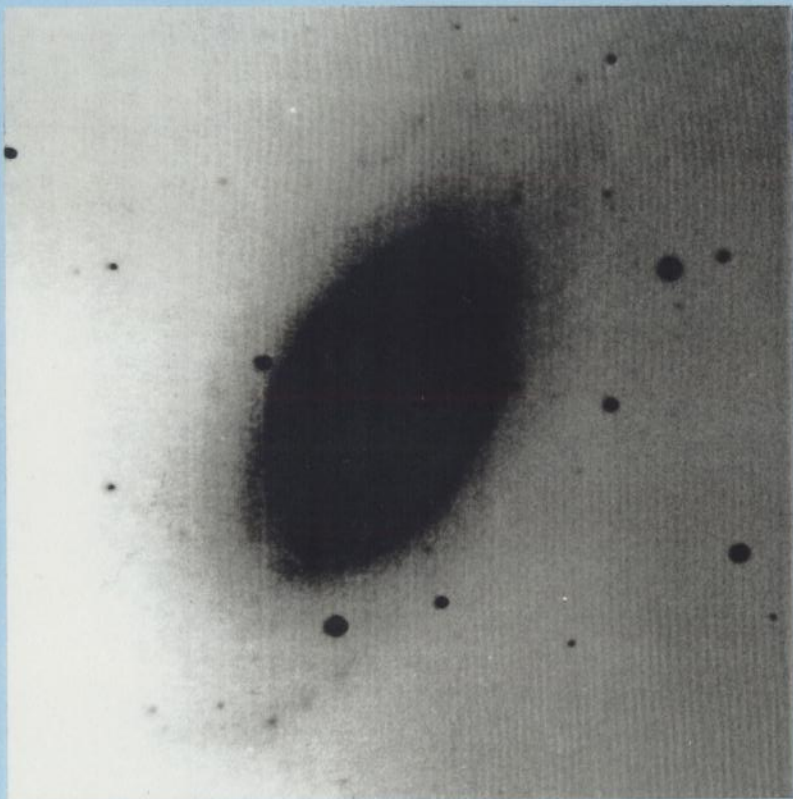
Maud et al. (2011) found $M_{ZAMS} = 13 \pm 3 M_{\odot}$

Van Dyk et al. (2011) found $M_{ZAMS} = 17 - 18 M_{\odot}$

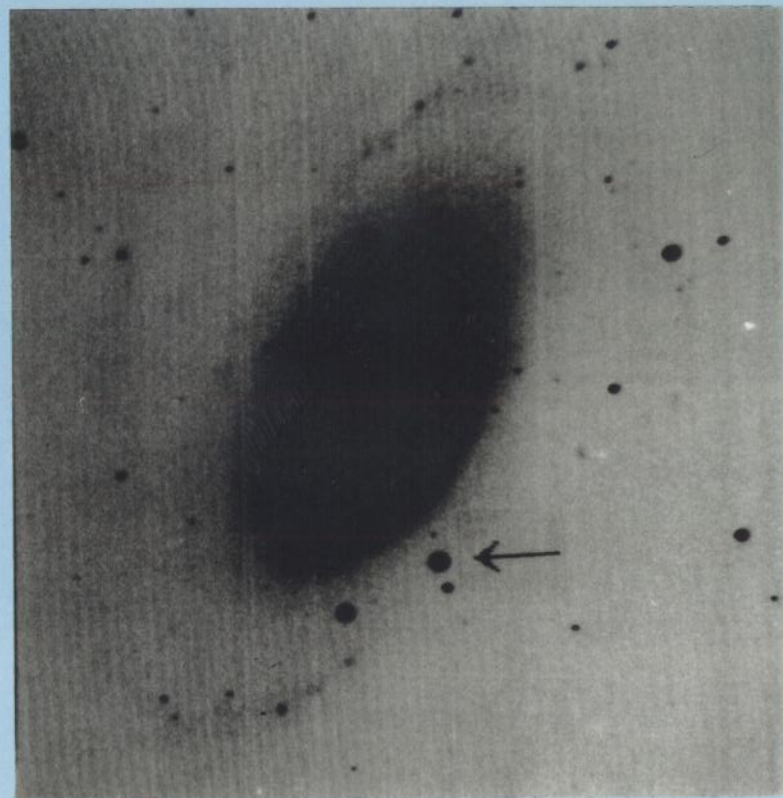
Stellar population analysis are in favor of lower mass estimation (Murphy+11)

Compact Progenitor ? clb

SN1993J in M81



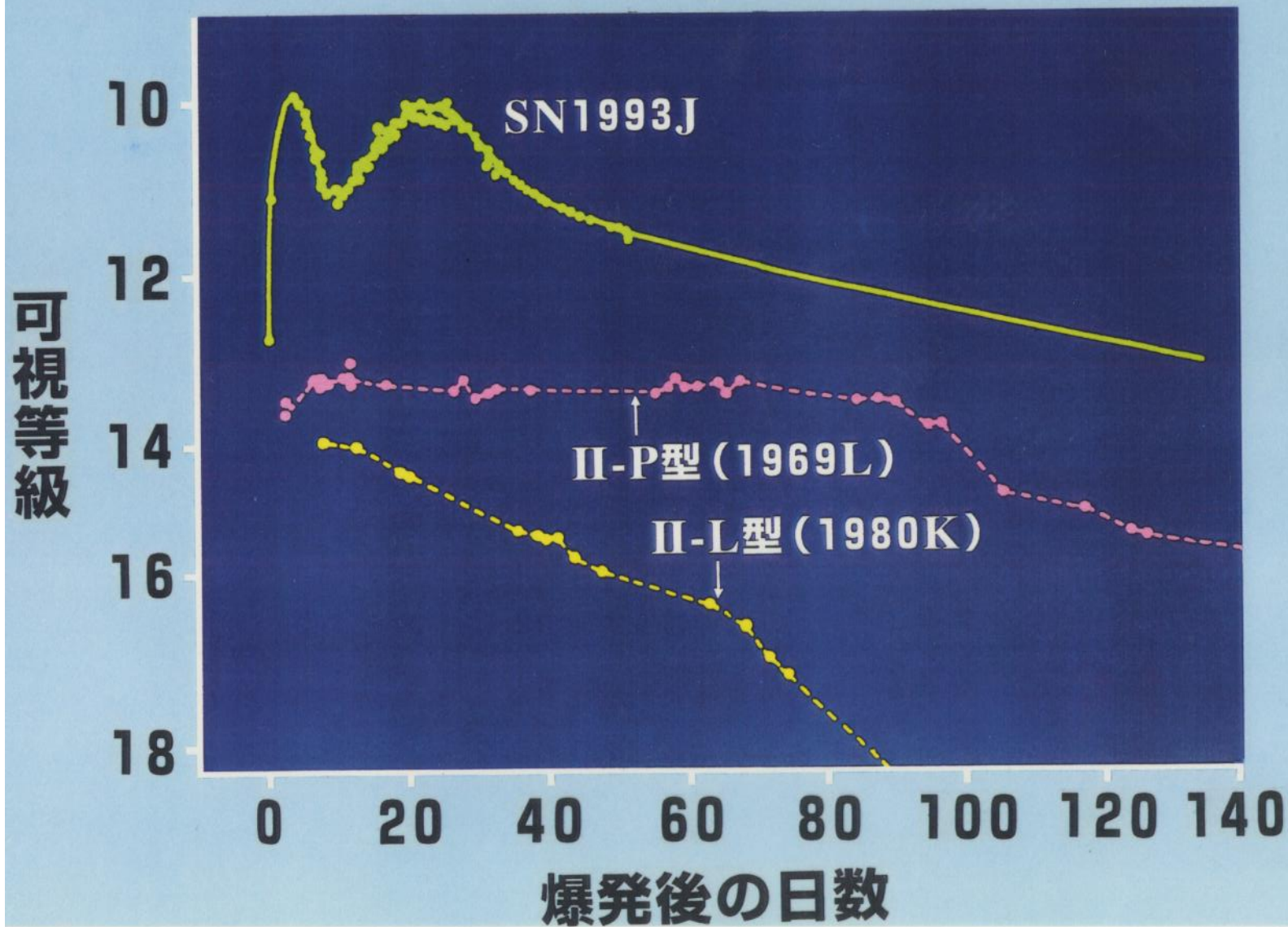
1993年3月25日



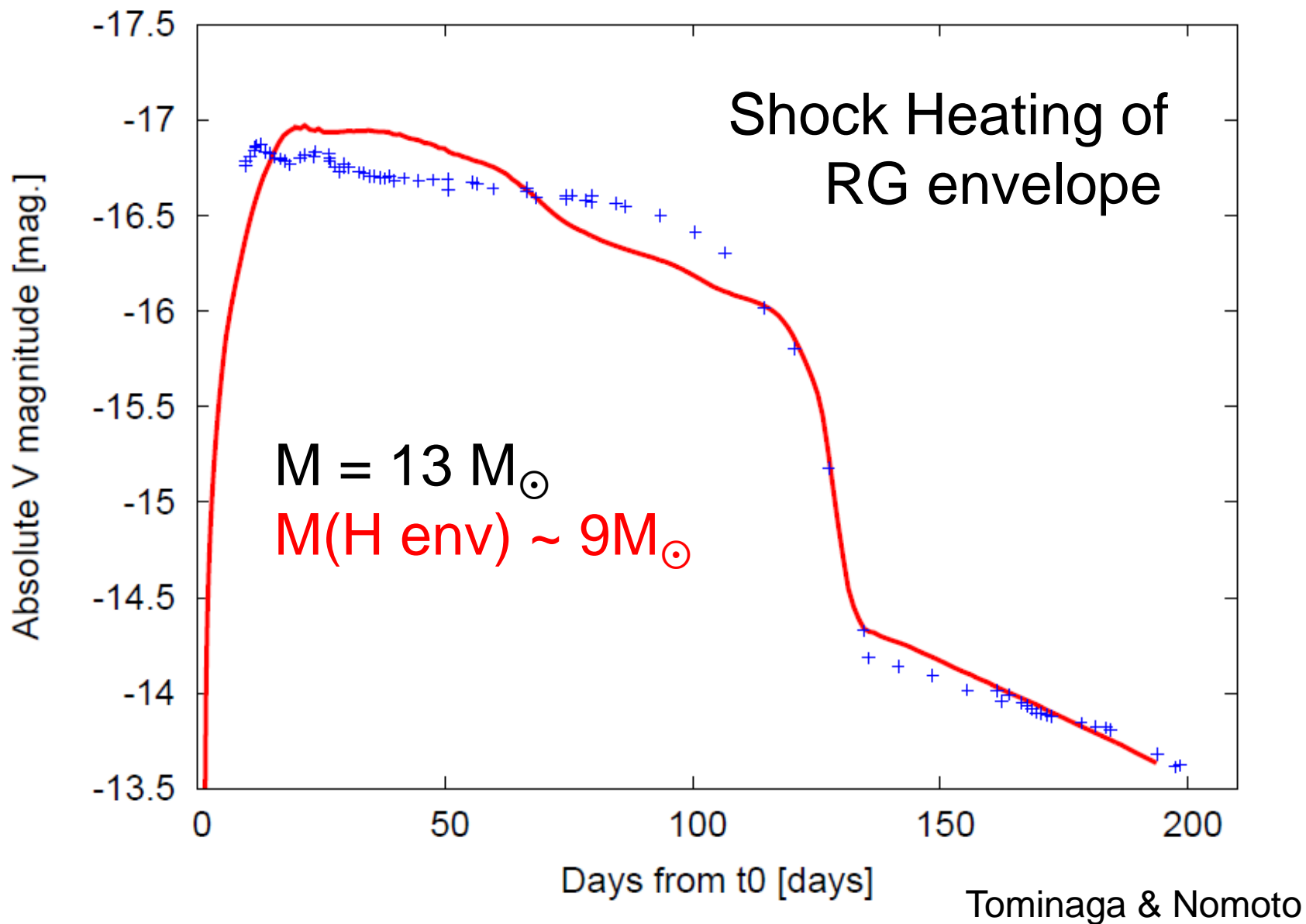
1993年3月31日

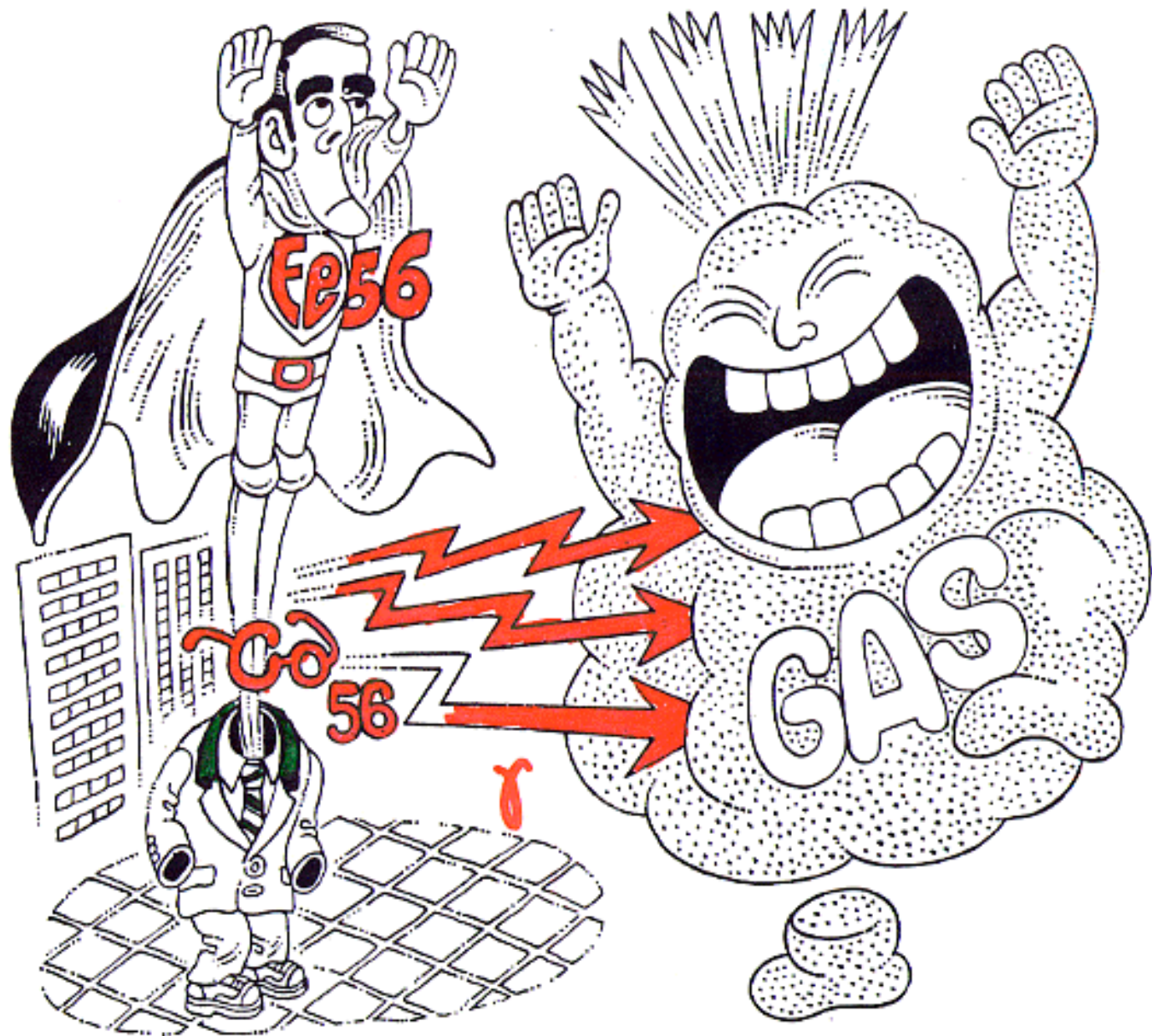
東京大学理学部木曾観測所

可視光の光度曲線



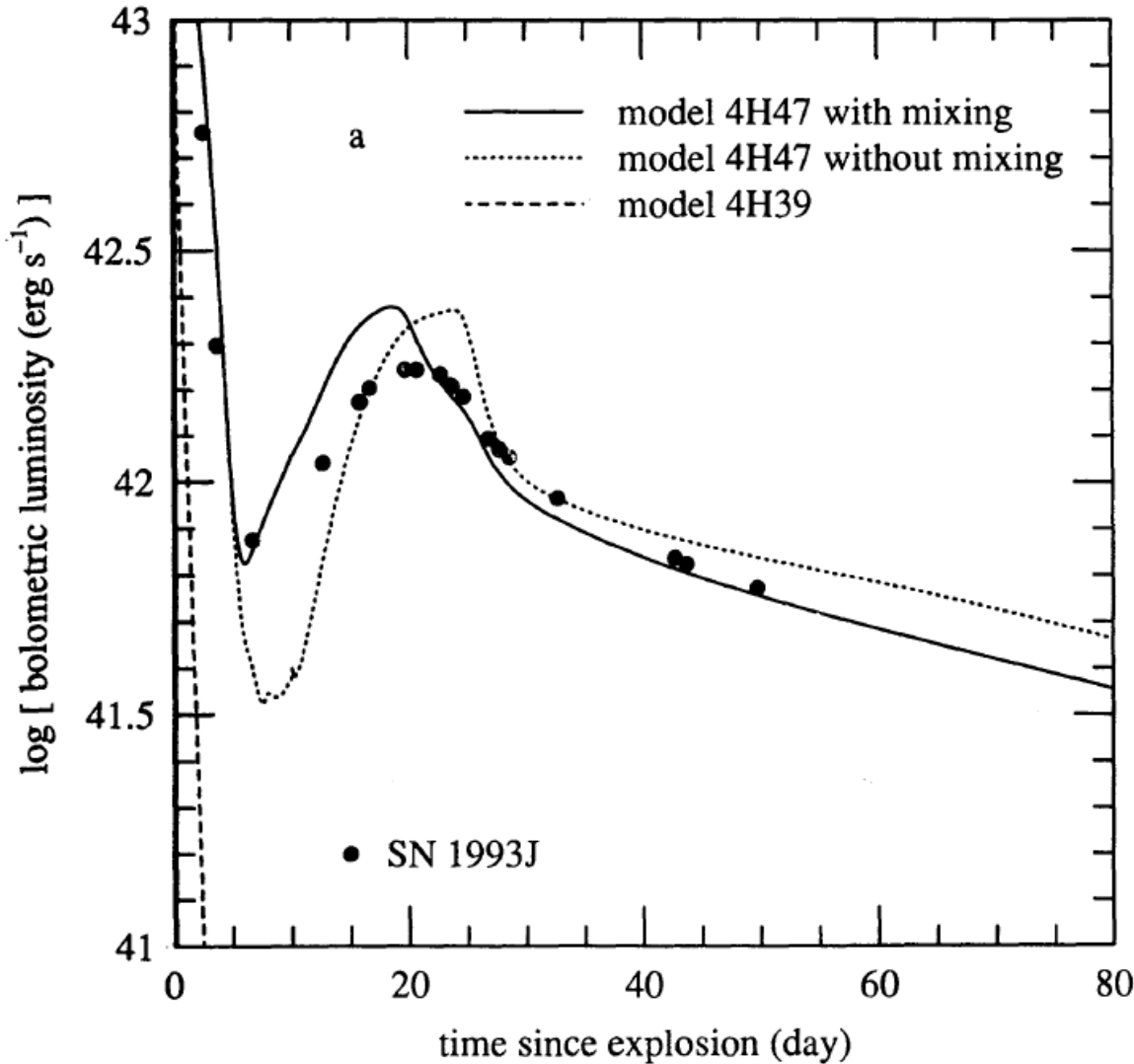
Light Curve Model for SN II-P





© Haruyo Nomoto

Light Curve Models for SN IIb 1993J



Progenitor
Red Giant

$$R \sim 400 R_{\odot}$$

$$M(\text{He}) = 4 M_{\odot}$$

$$M(\text{H}) = 0.47 M_{\odot}$$

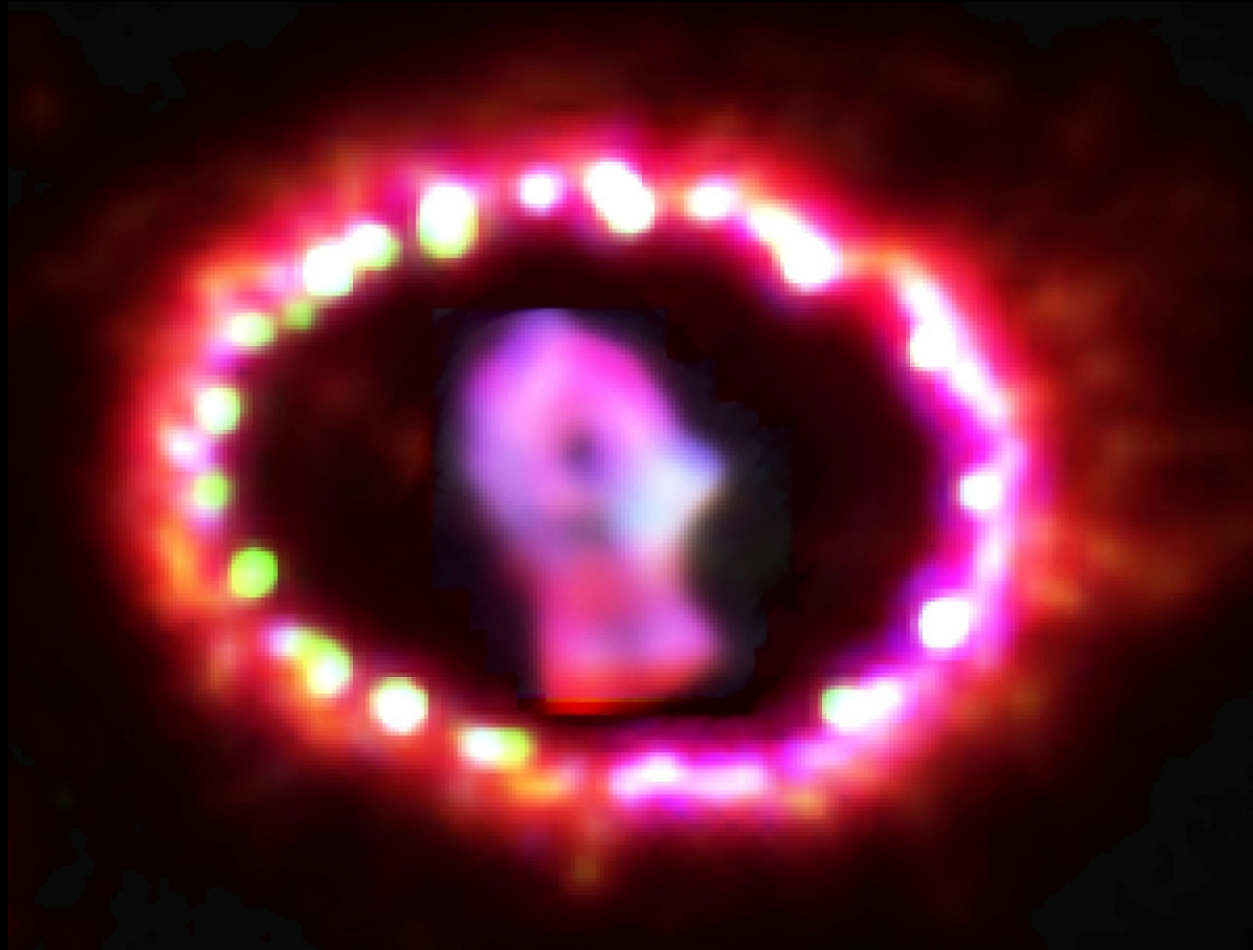
He-rich

1st peak :
Shock Heating

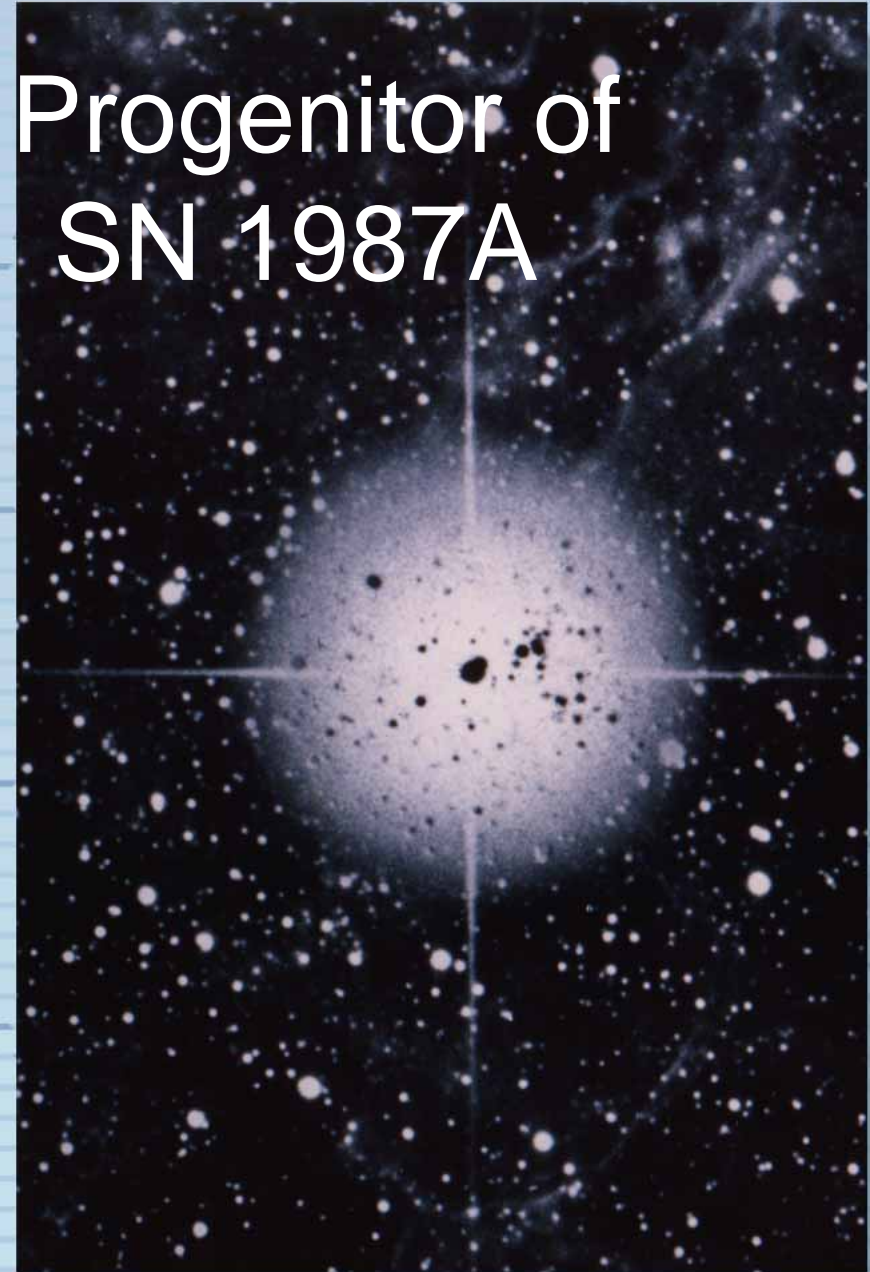
2nd peak :
⁵⁶Ni-⁵⁶Co decay

Shigeyama, Nomoto (94)

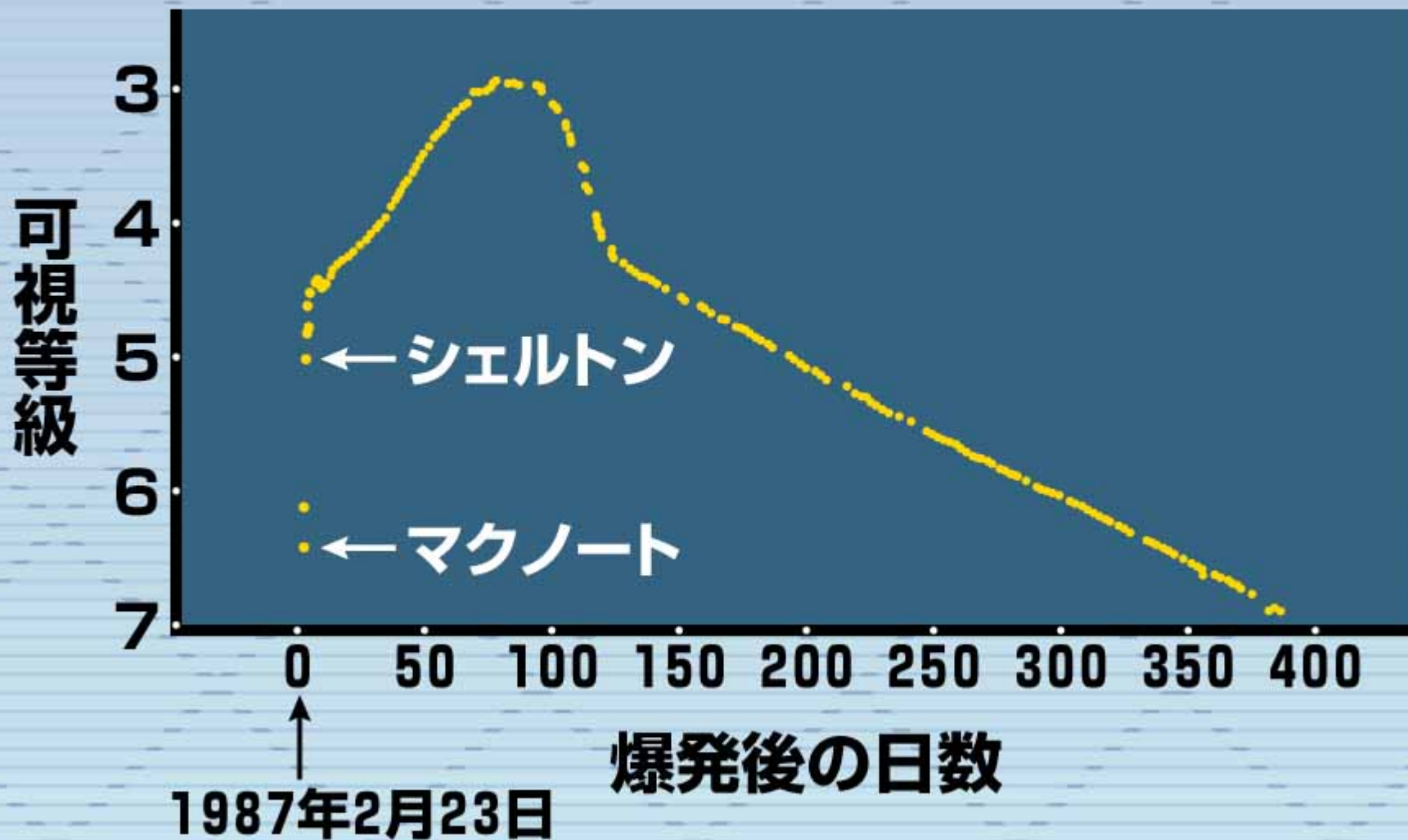
SN 1987A



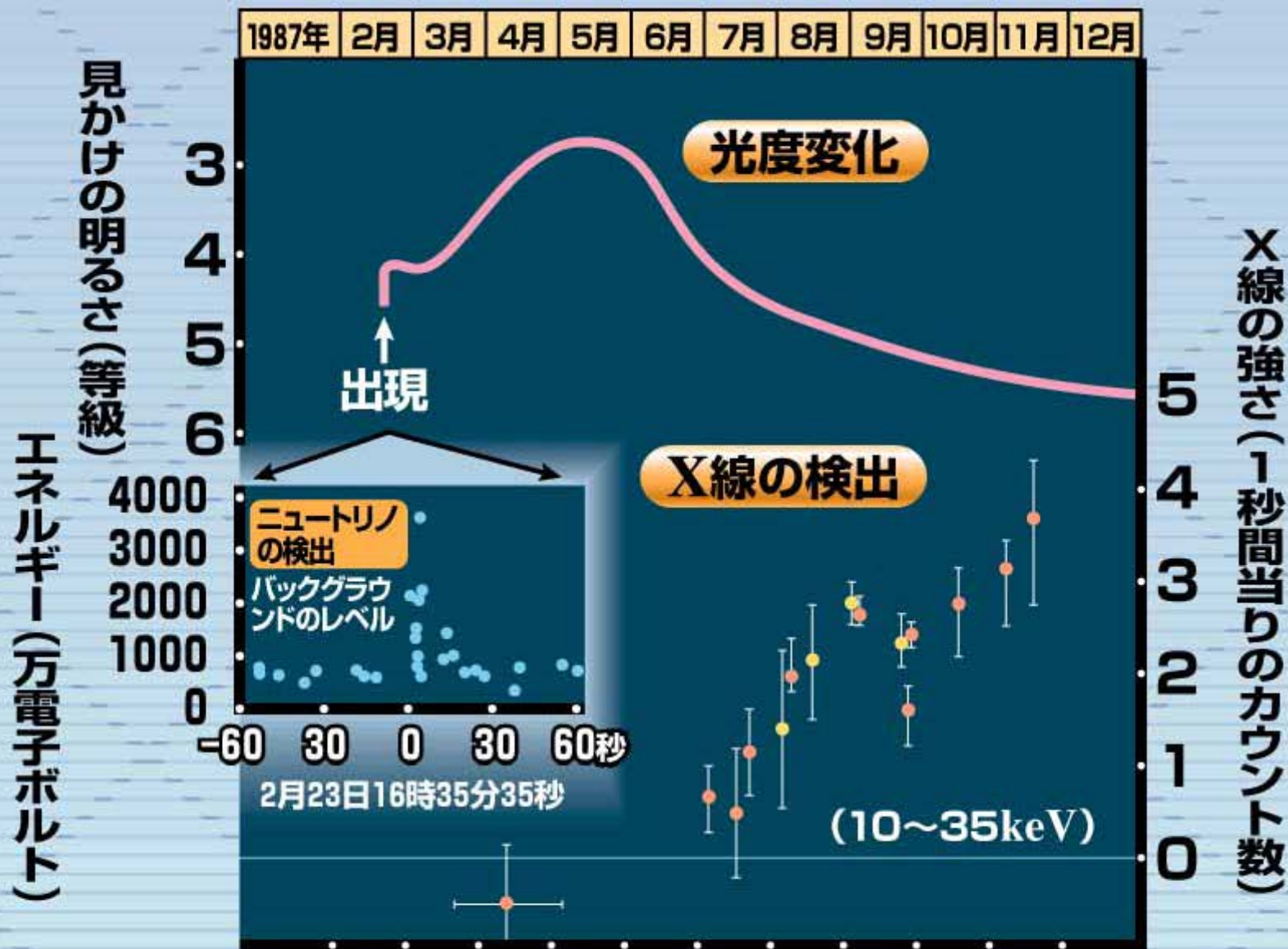
Blue Supergiant Progenitor of SN 1987A



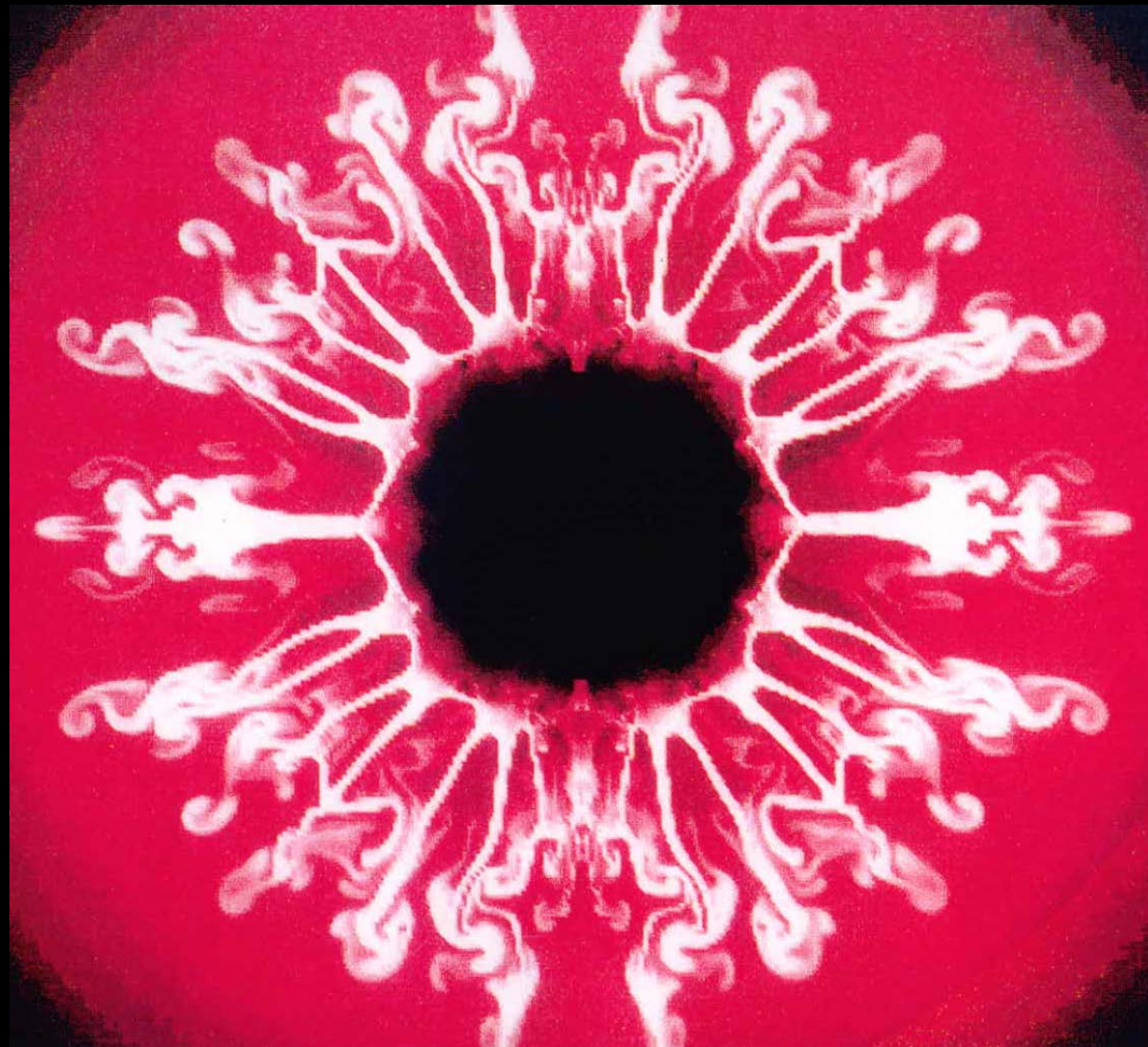
超新星1987Aの光度曲線



SN1987A

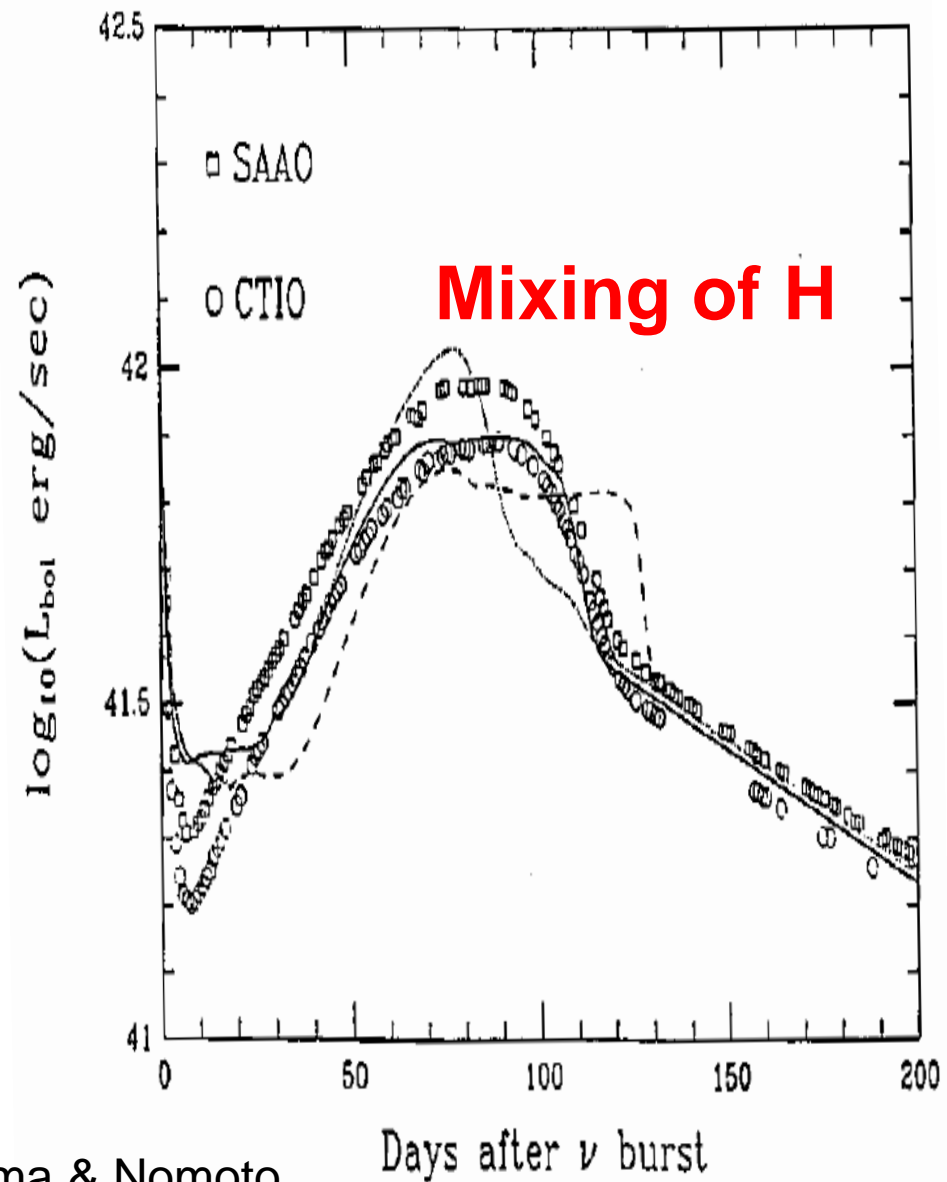
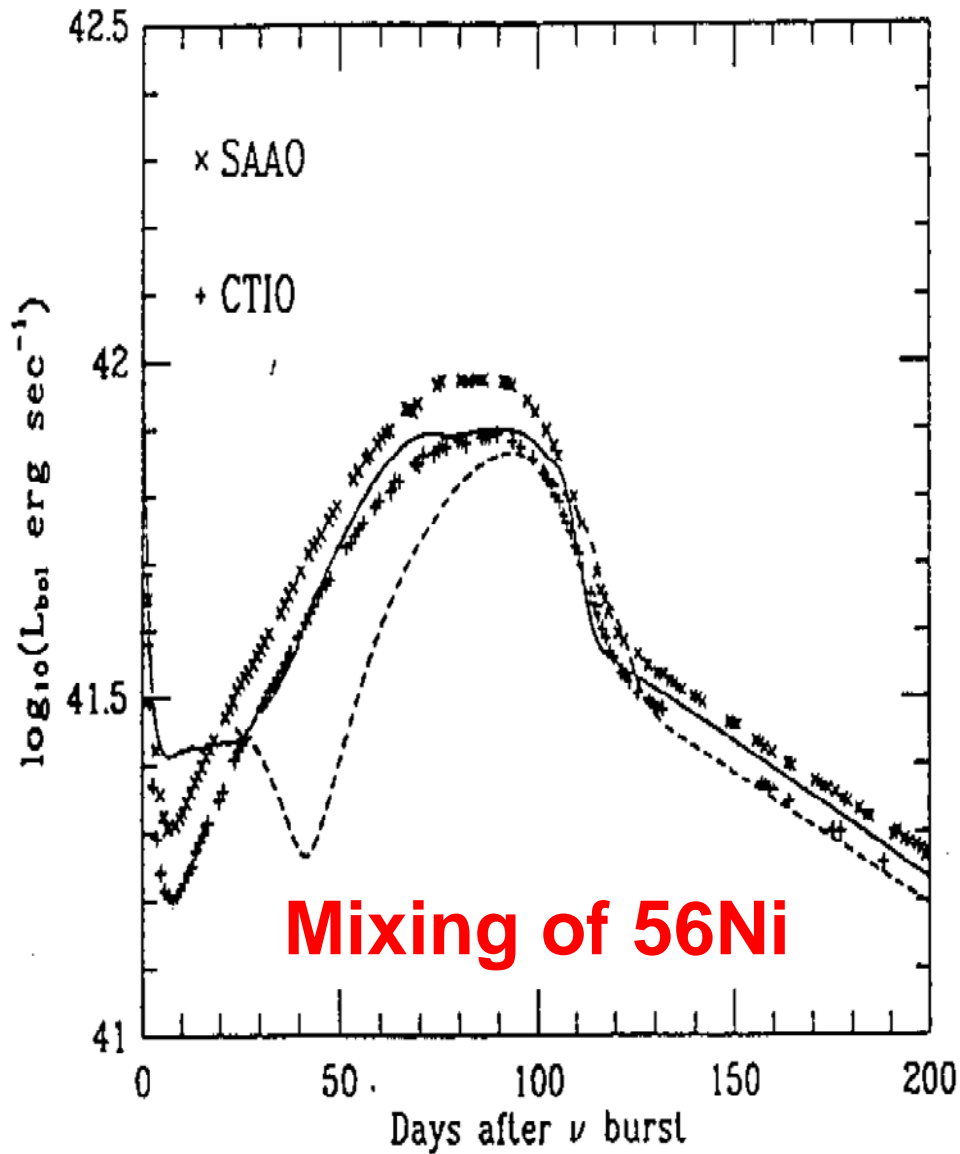


SN1987A



Hachisu, Nomoto et al

Mixing and Light Curve of SN 1987A



Light Curves of 1993J & 1987A

- First peak:

Shock heating in the RG envelope

SN 1993J : short ← $M(H) < 1 M_{\odot}$

$R \sim 400 R_{\odot}$

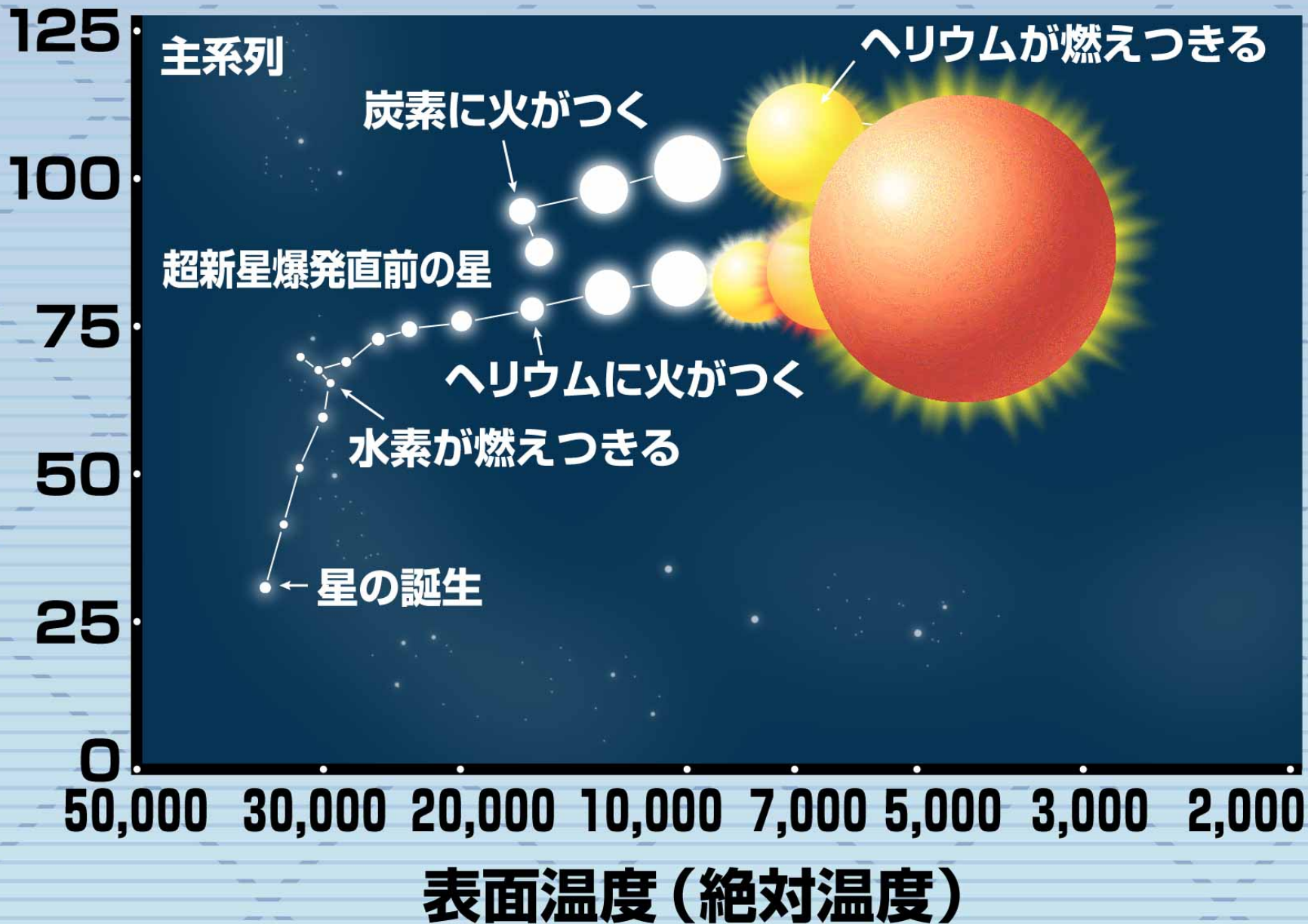
SN 1987A: faint ← small radius: $50 R_{\odot}$

$M(H) \sim 10 M_{\odot}$

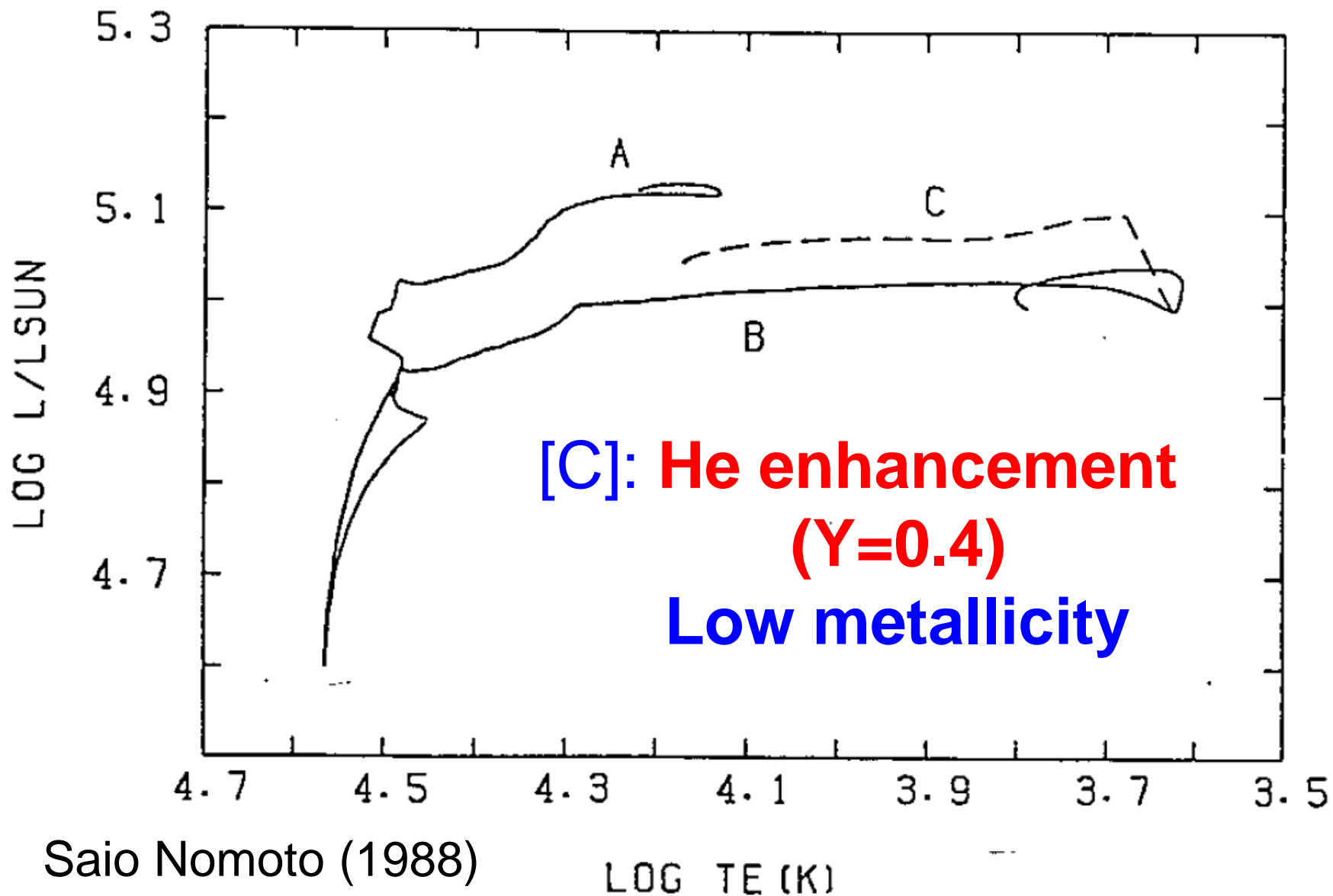
- Second peak: radioactive decays

爆発した星の一生

光度(太陽光度の1000倍)

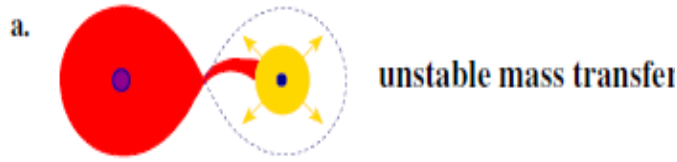


SN 1987A : Blue → Red → Blue

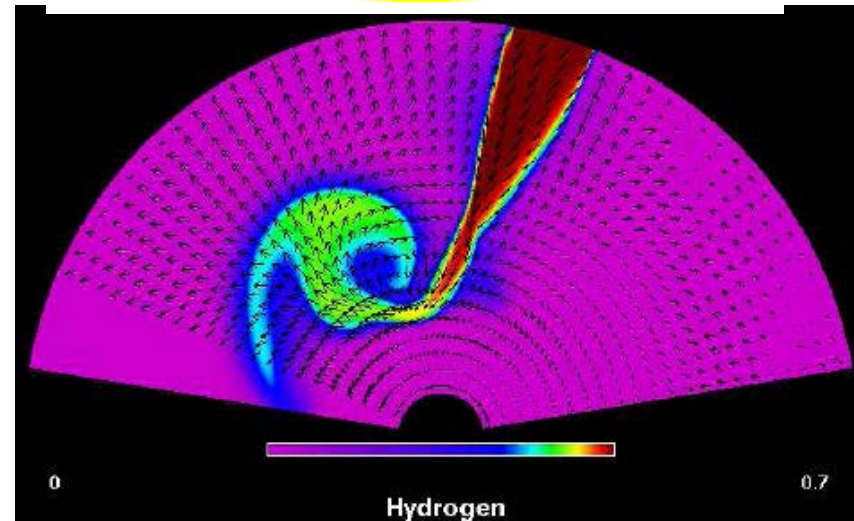
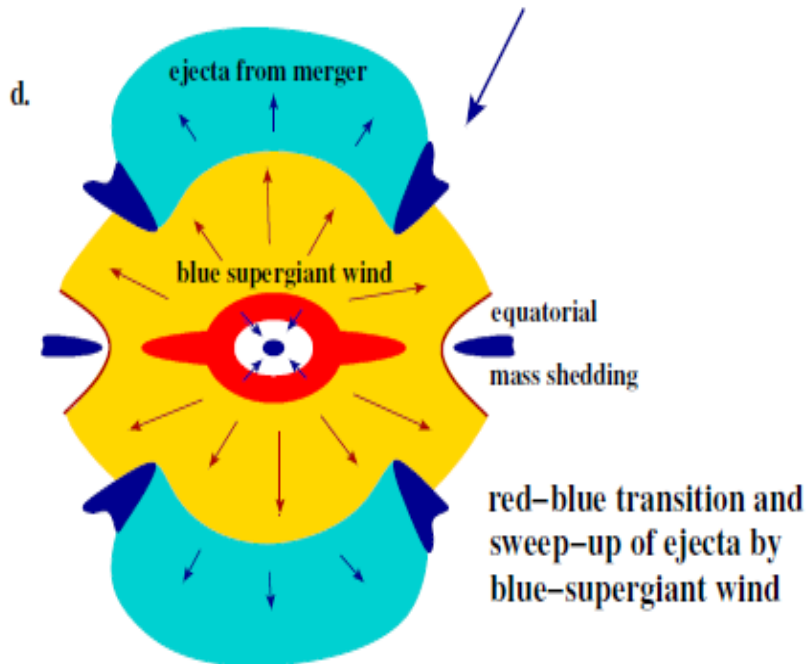
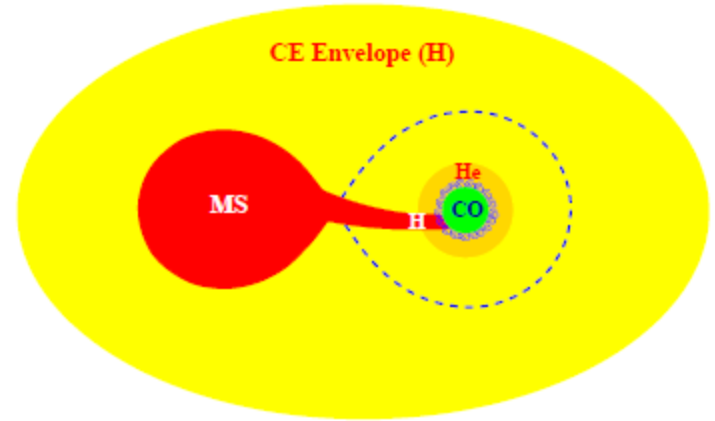
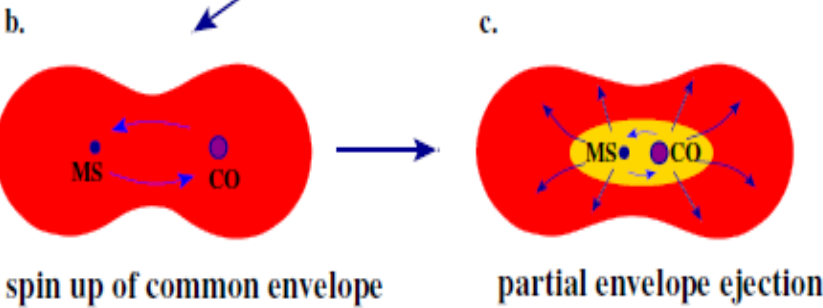


“Red to Blue” in Binary Scenario

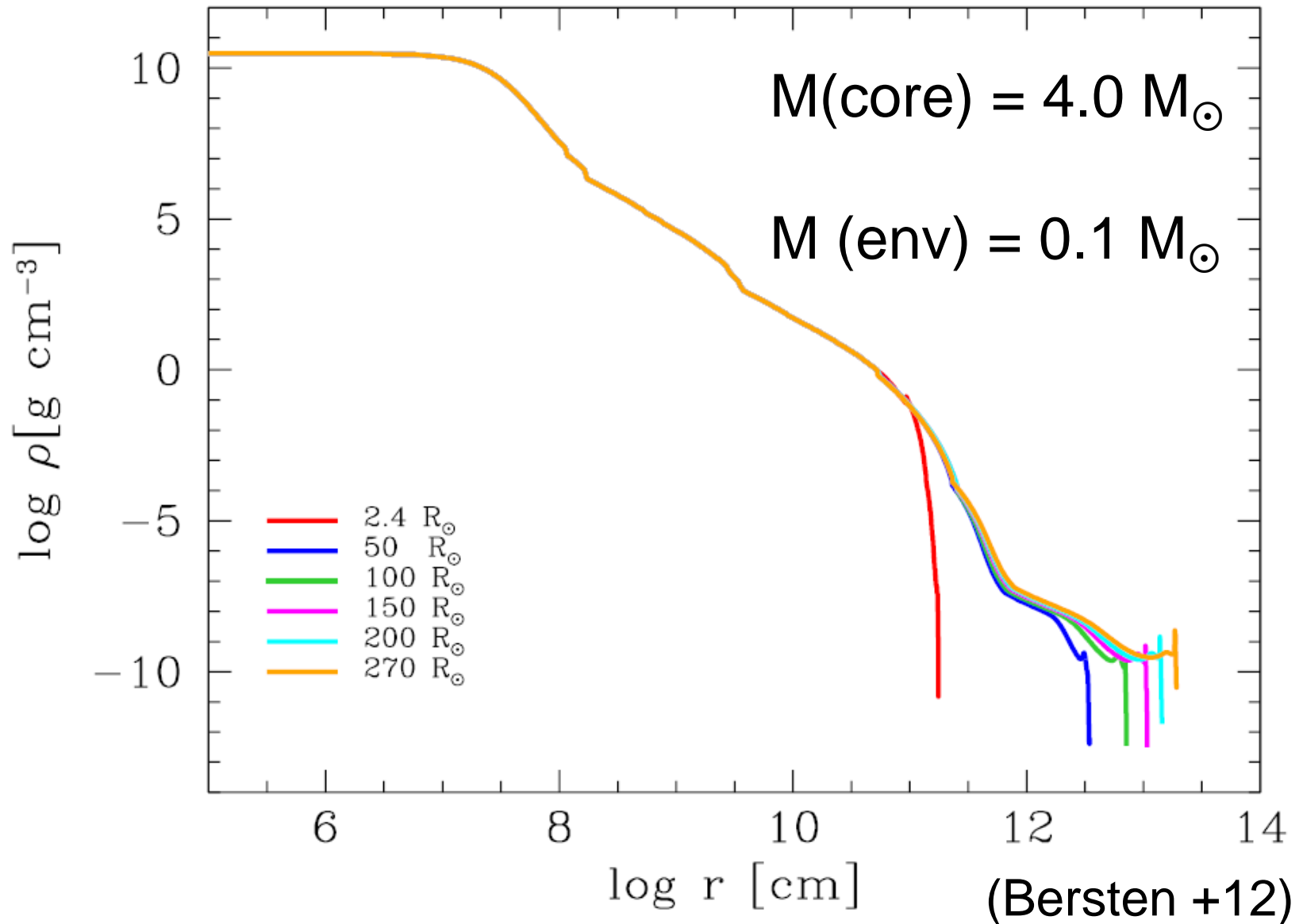
(Podsiadlowski 2007)



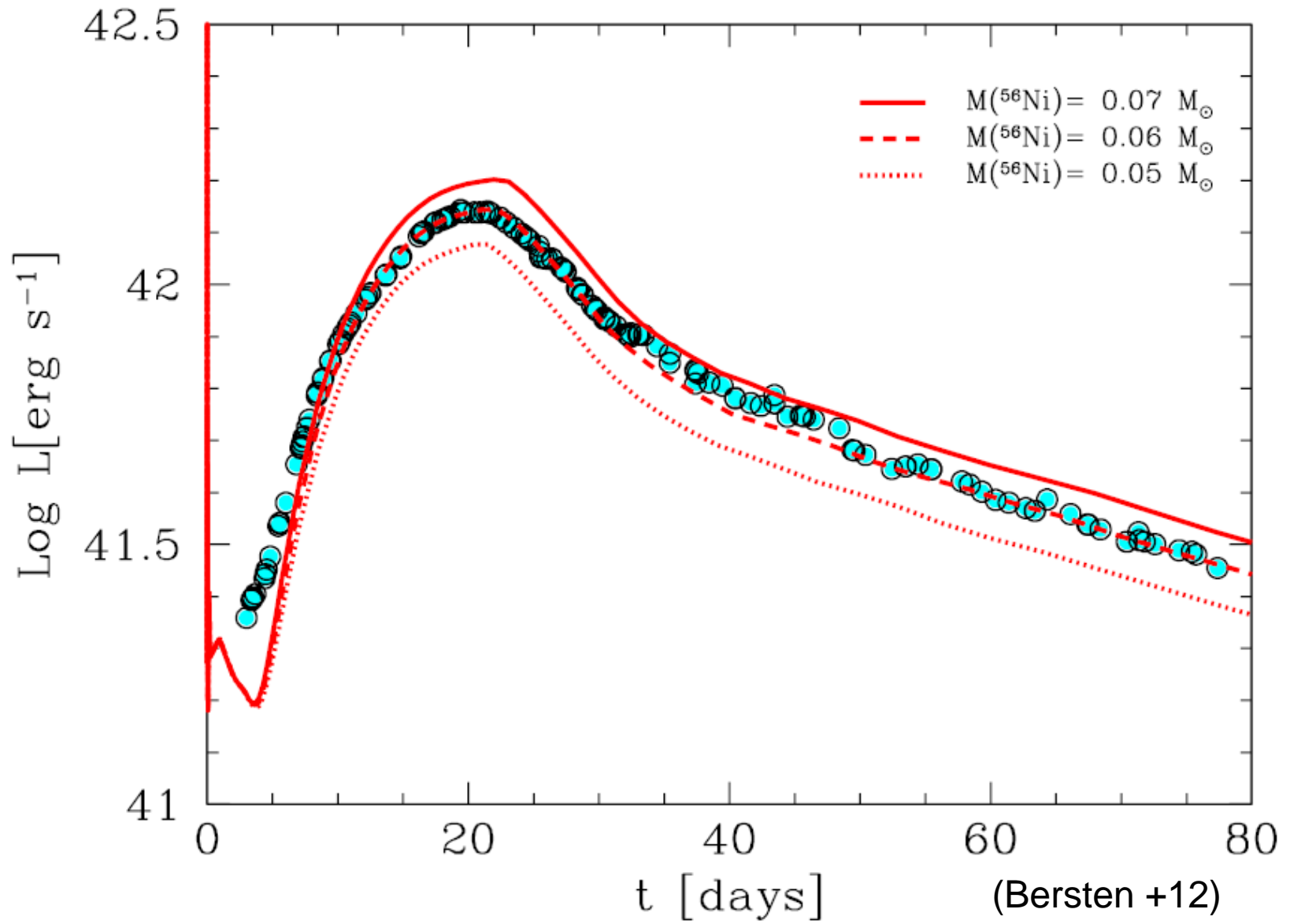
- stream impacts with helium core → core penetration ($\sim 10^{10}$ cm) → dredge-up of helium



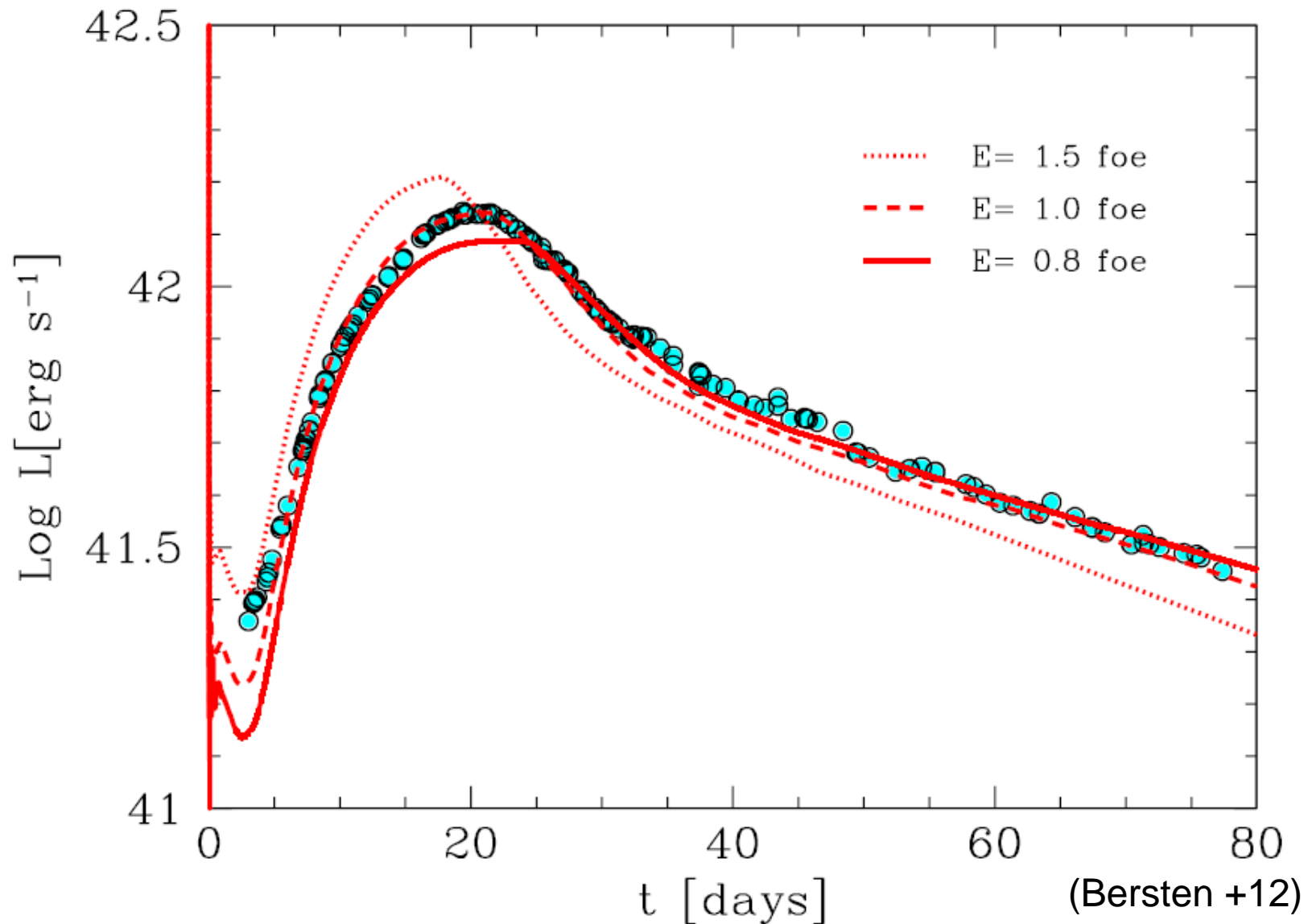
SN IIb 2011dh: Progenitor Models



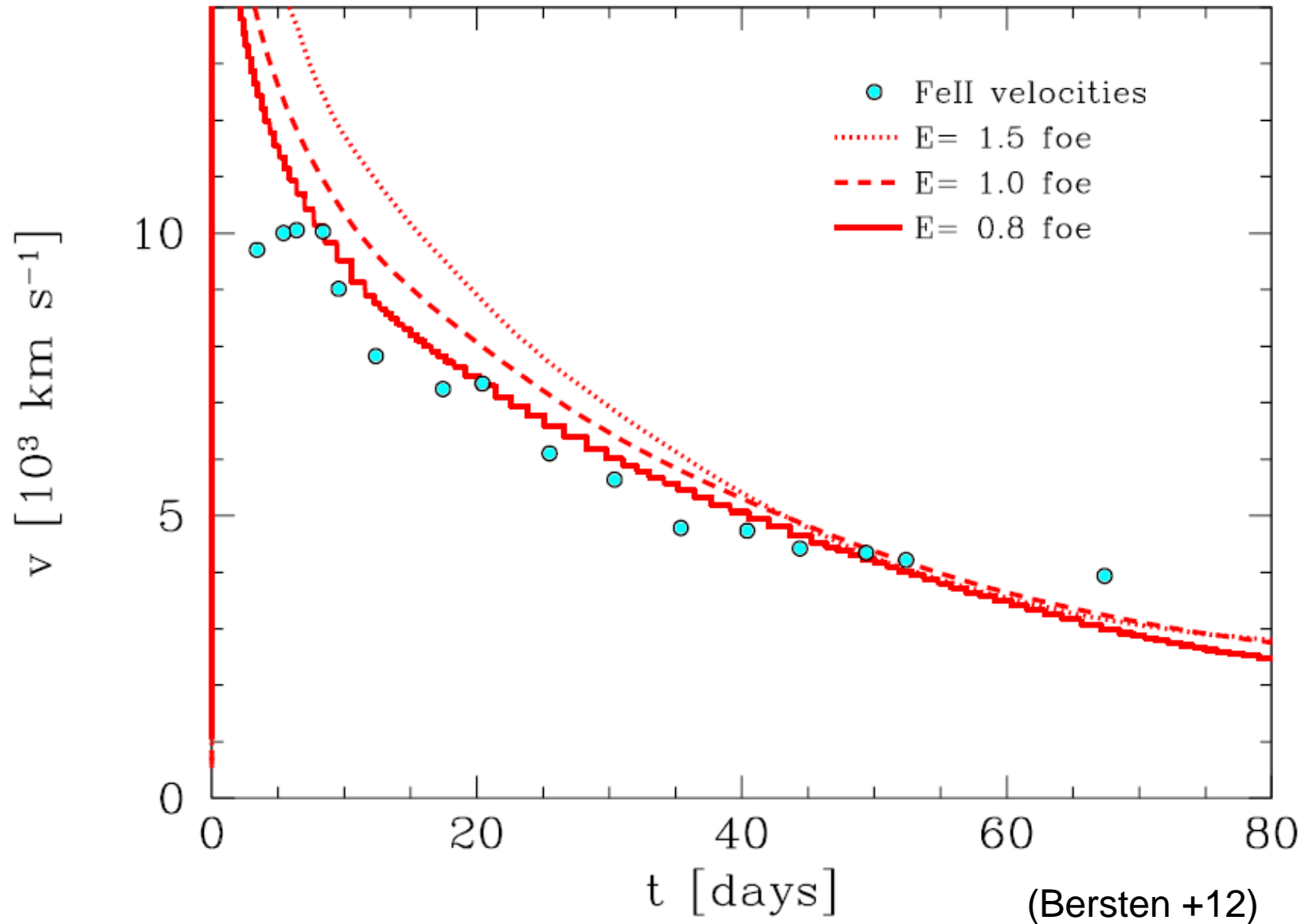
SN Iib 2011dh: Mass of ^{56}Ni



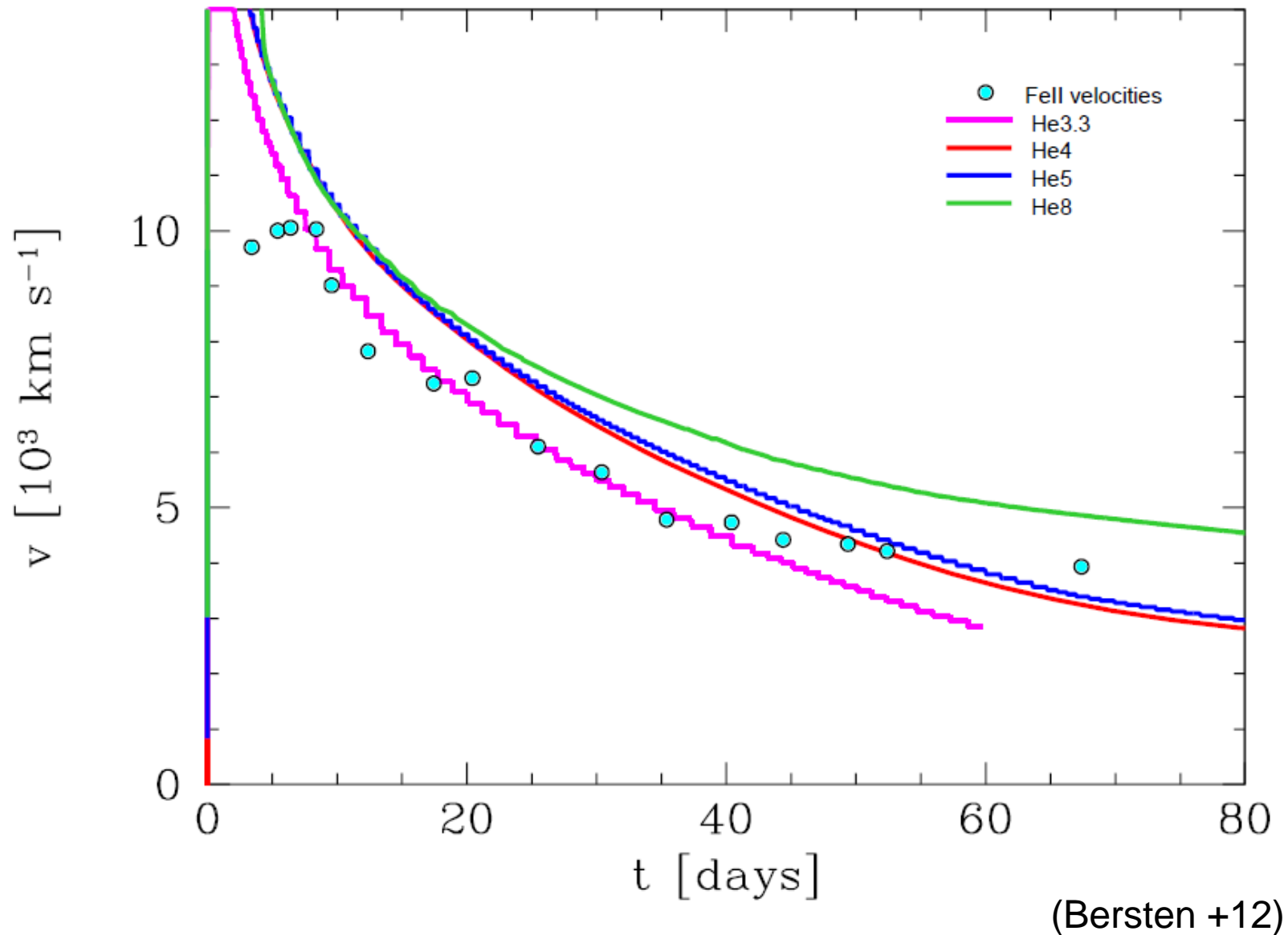
SN IIb 2011dh: Explosion Energy



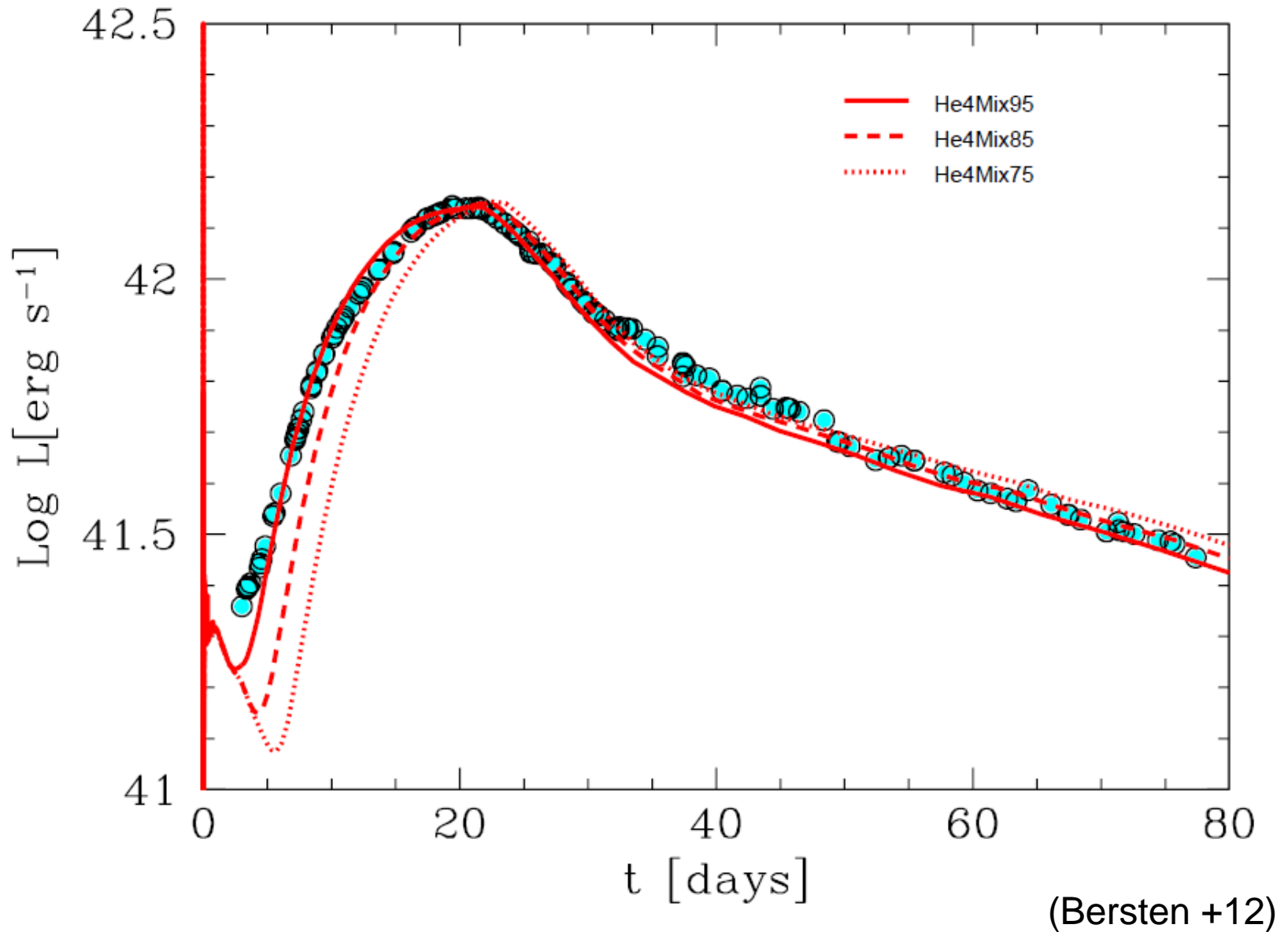
SN IIb 2011dh: Explosion Energy



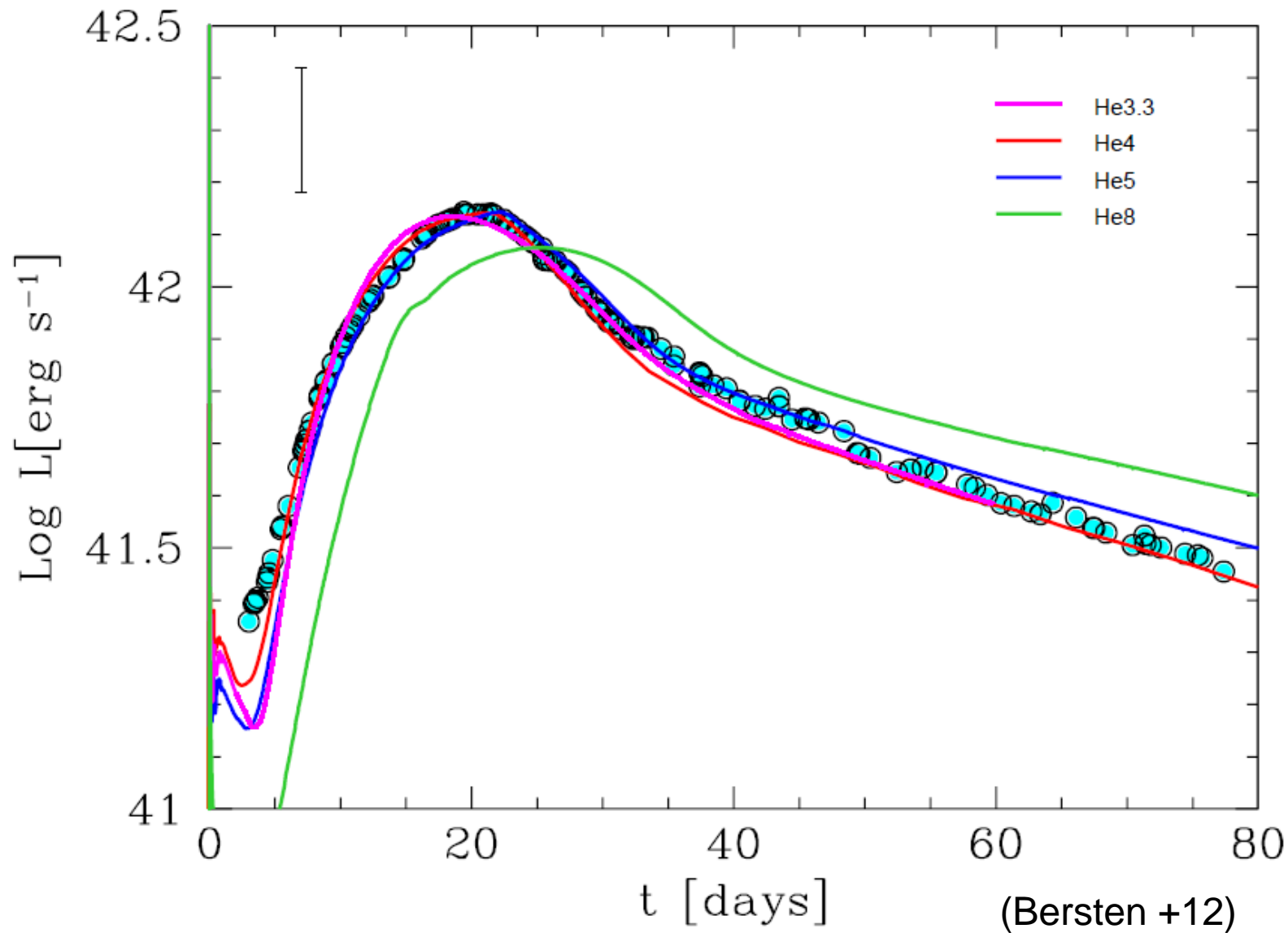
SN IIb 2011dh: E & Mass



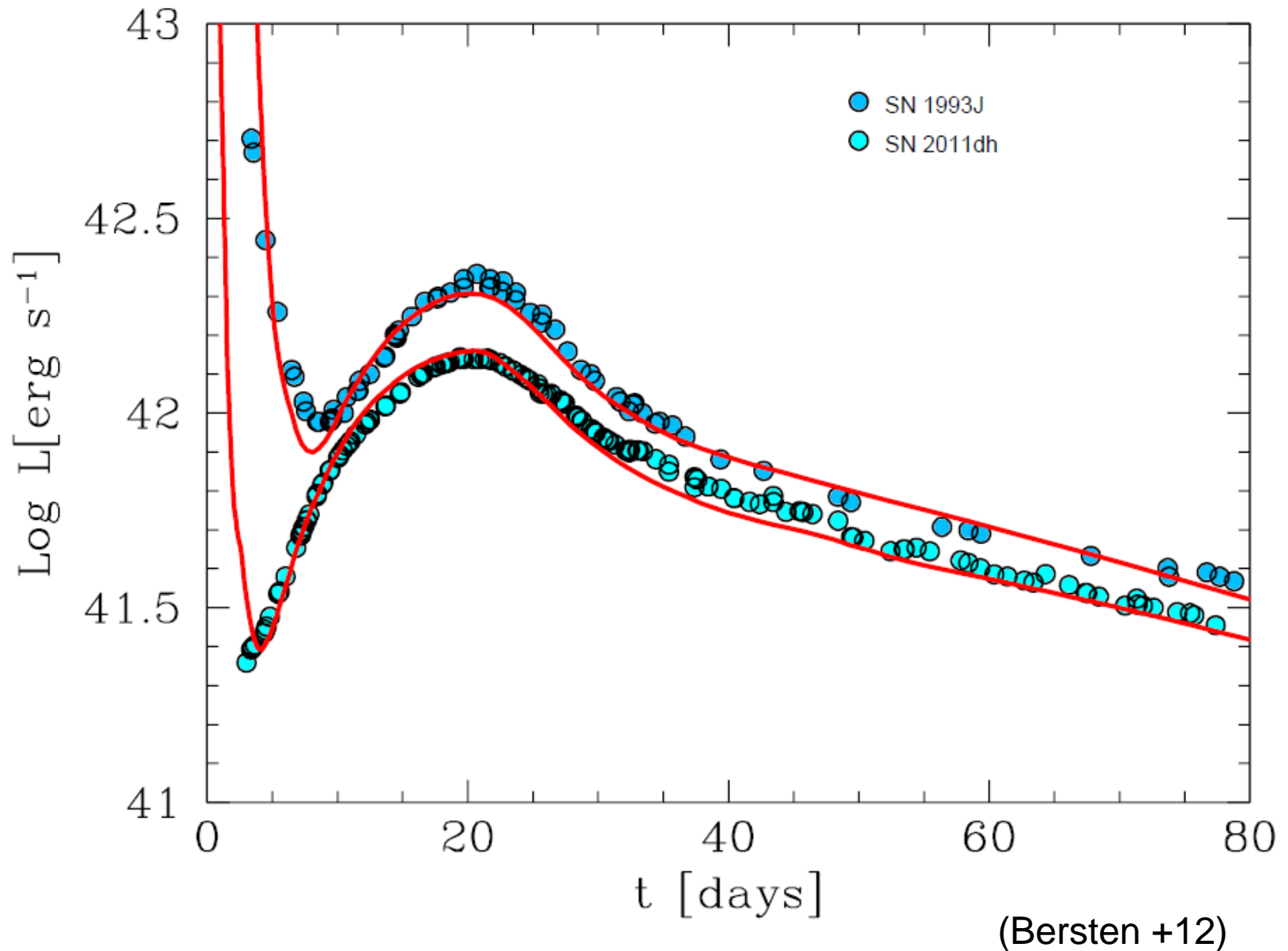
SN Iib 2011dh: Mixing of ^{56}Ni



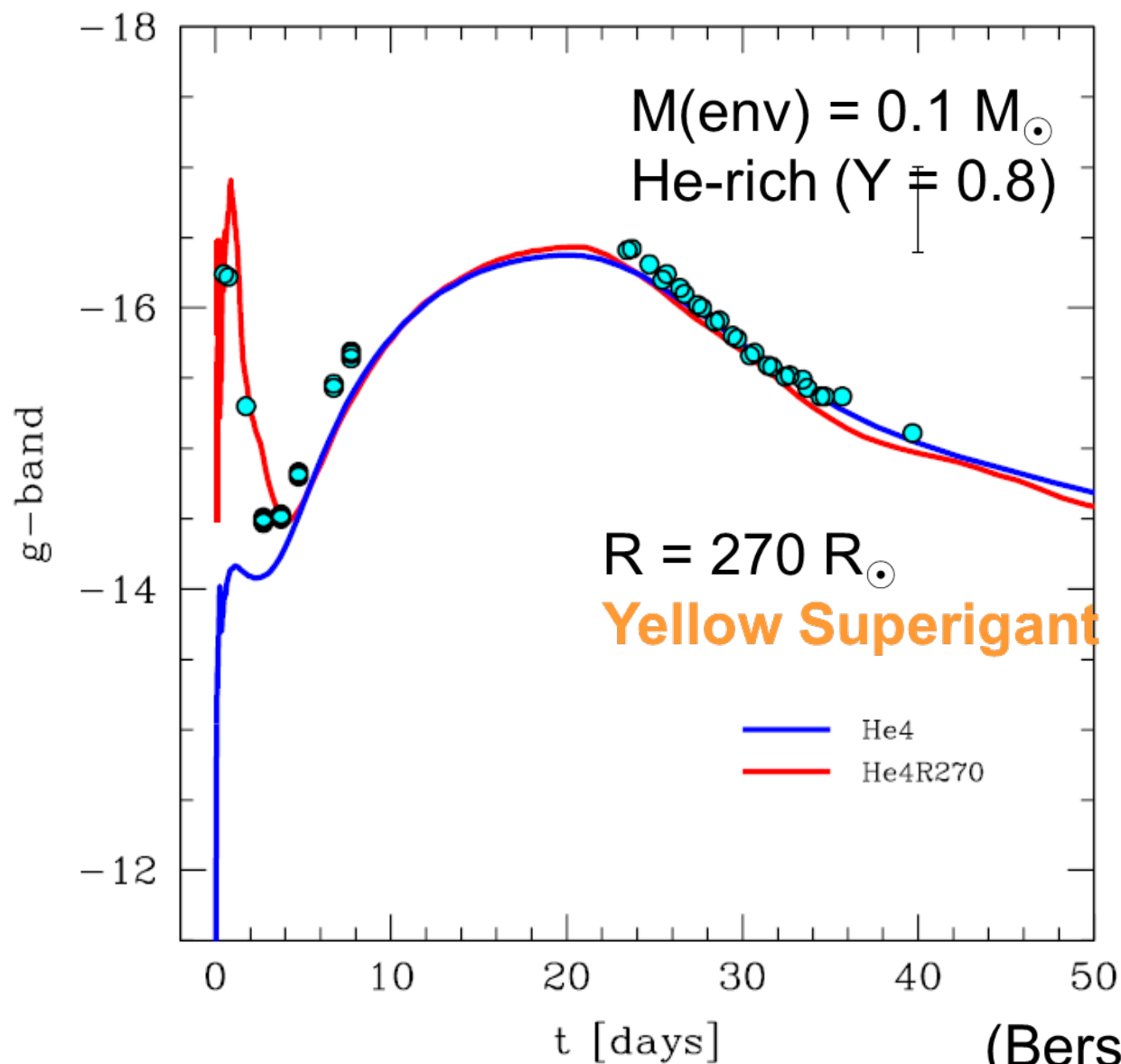
SN IIb 2011dh: He Core Mass



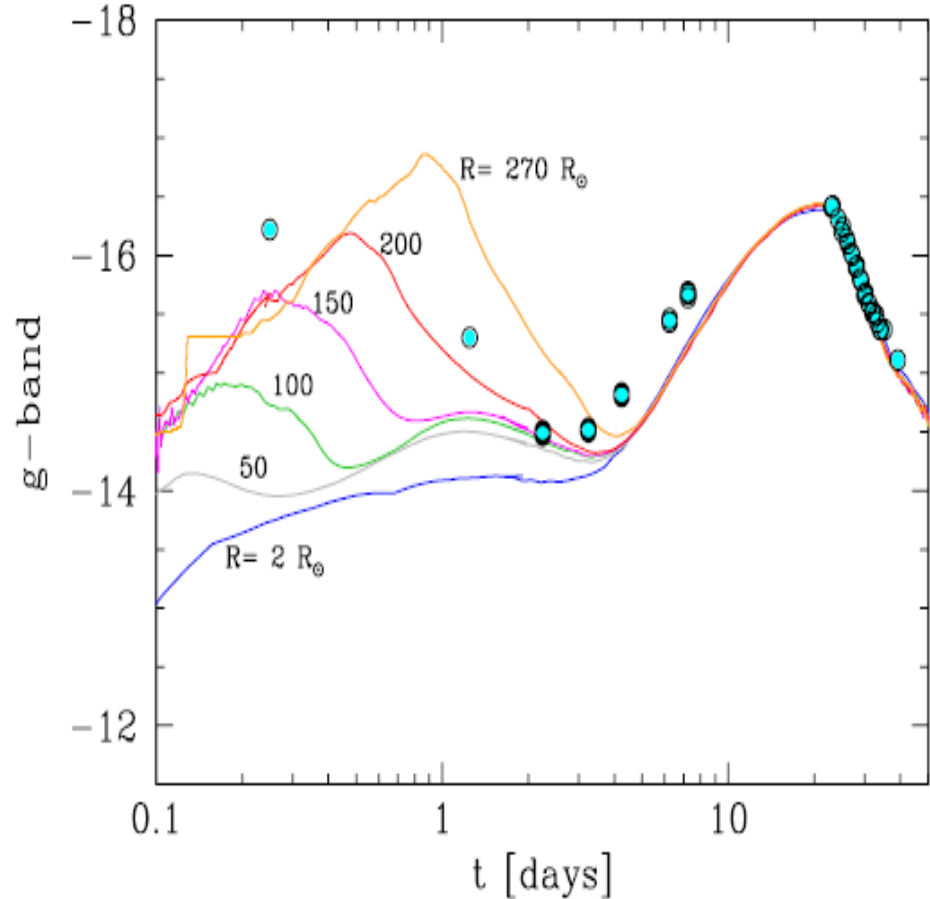
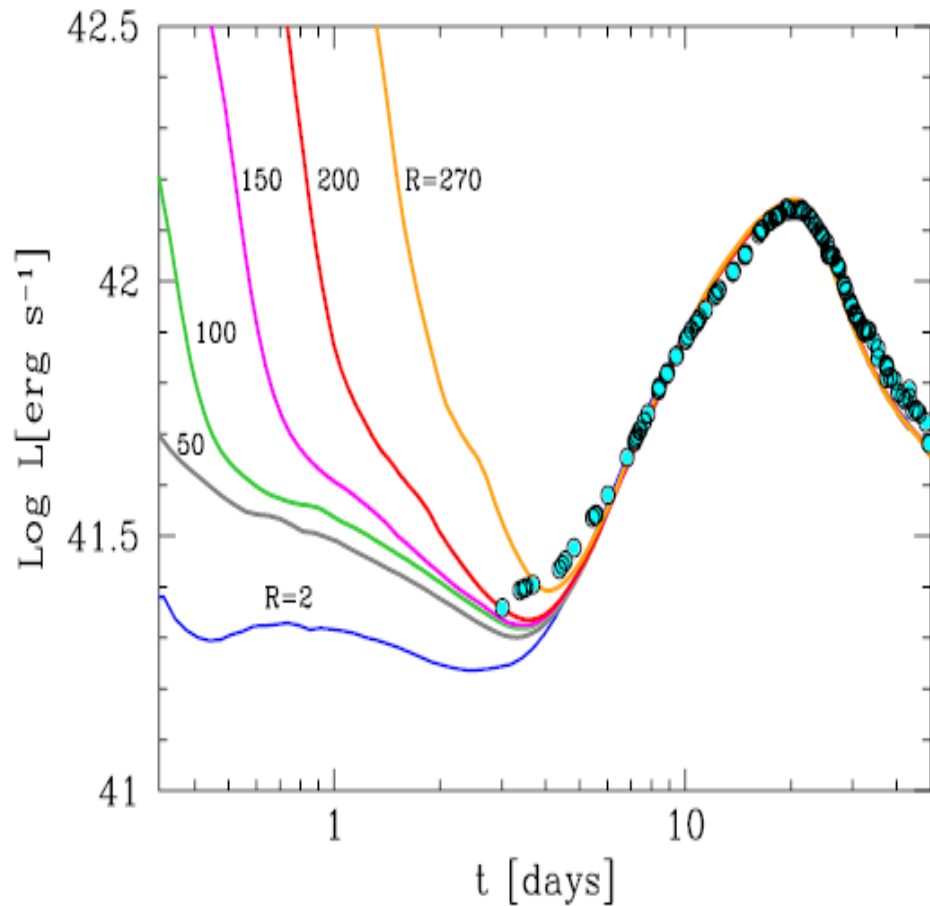
SN IIb1993J



SN I Ib 2011dh: Double Peak LC



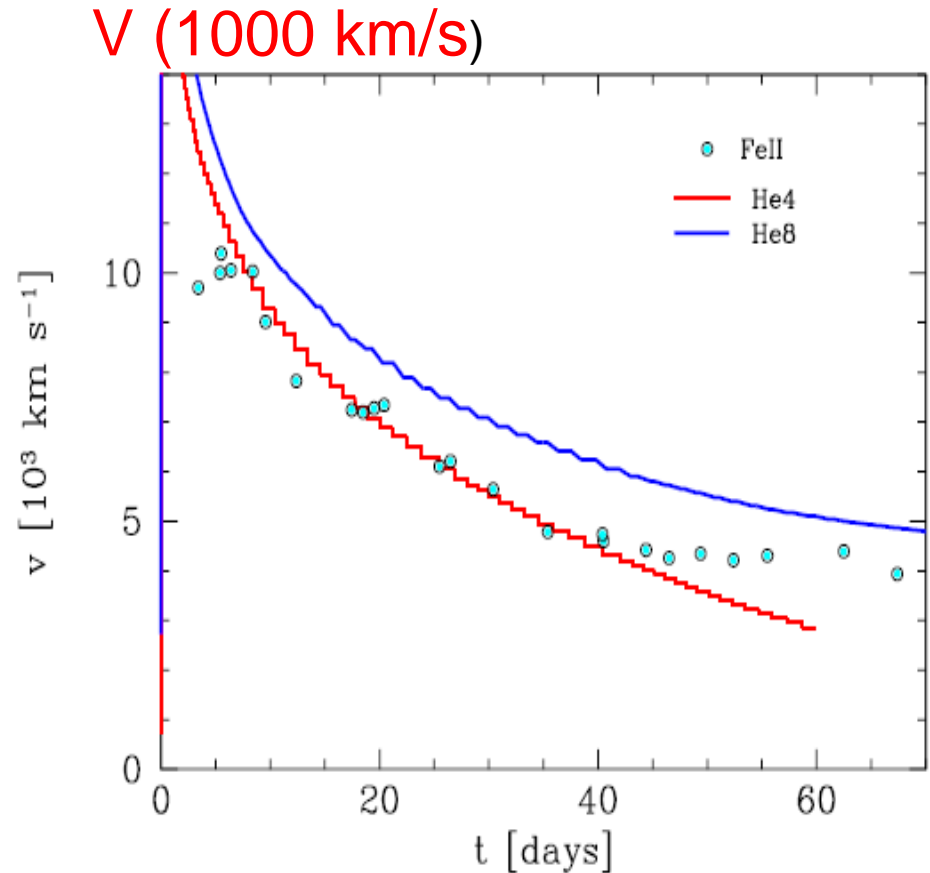
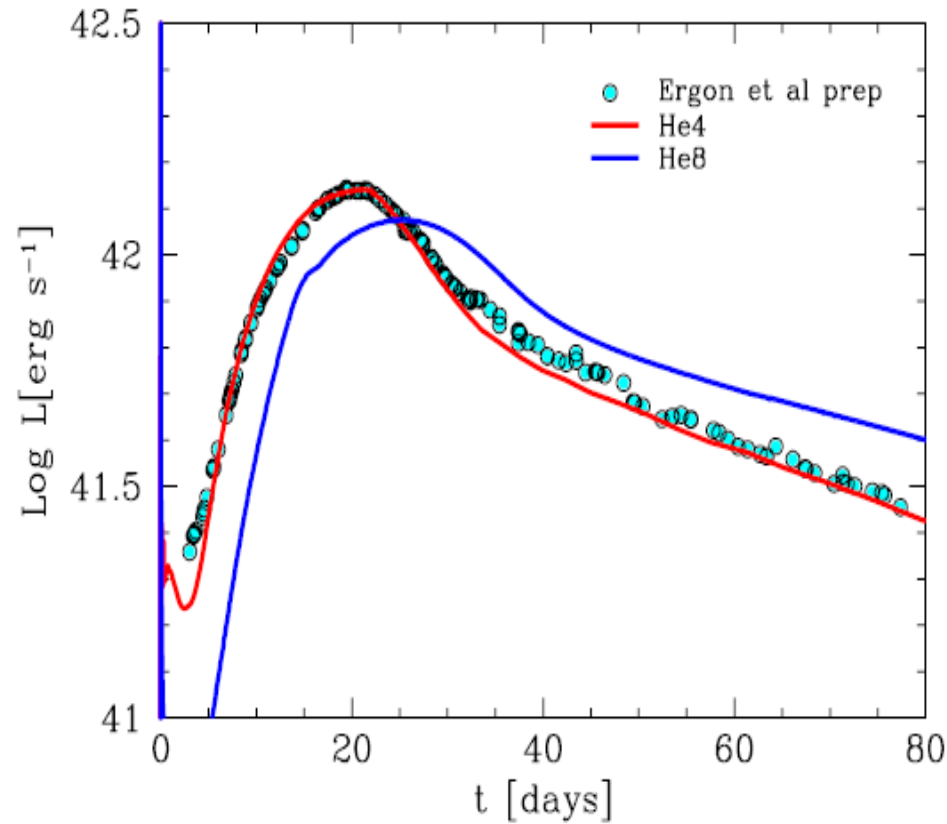
Light Curve of SN IIb 2011dh (Progenitor's Radius)



Models with $R \gtrsim 150 R_{\odot}$ are required (Bersten+ 2012)

SN IIb 2011dh : LC & vel(ph)

$M(\text{ms}) < 18 M_{\odot}$; $M(\text{He}) < 5 M_{\odot} \rightarrow \text{Binary}$



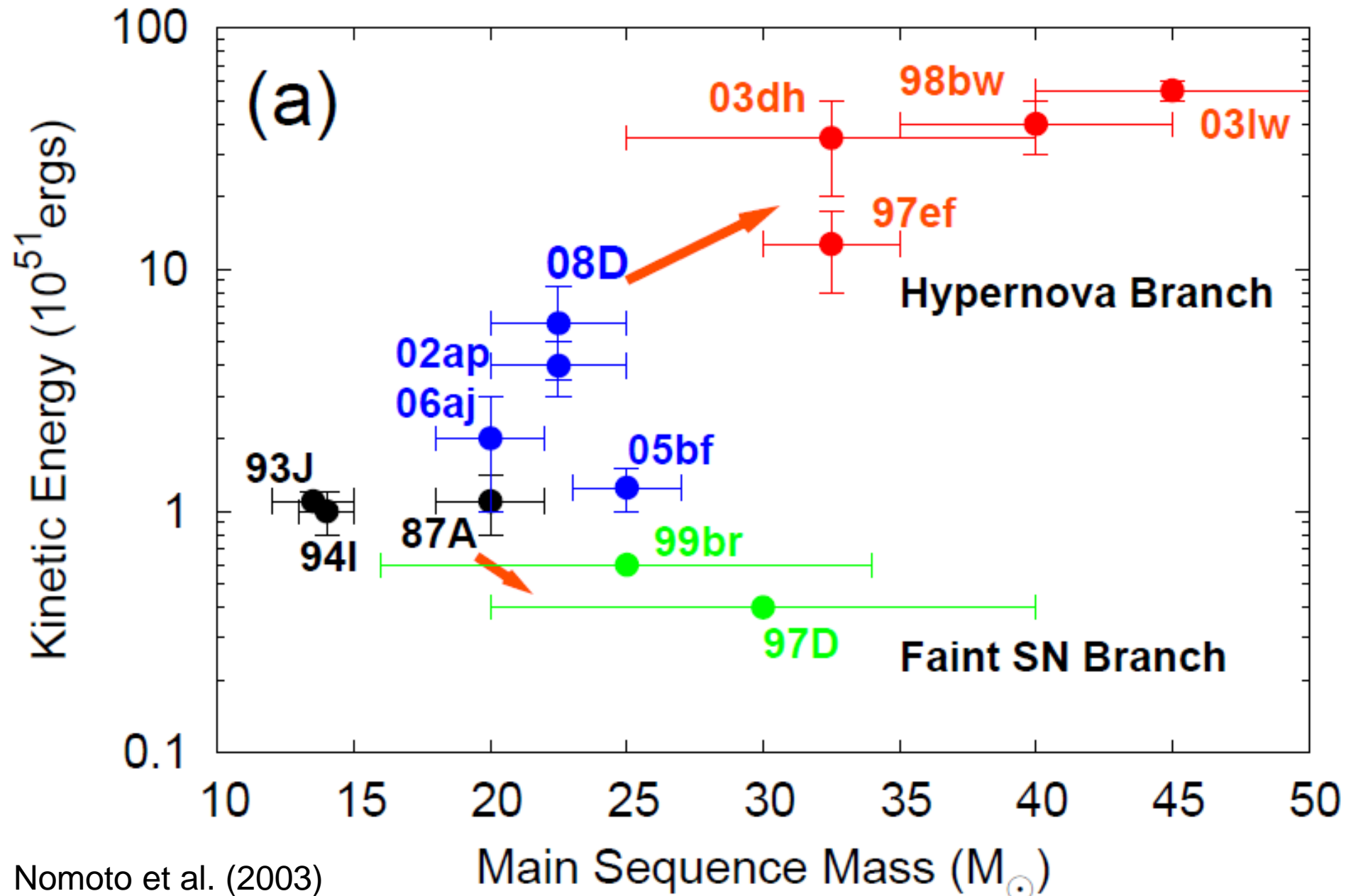
Optimal model: He core mass $\sim 4 M_{\odot}$ ($M_{\text{ZAMS}} = 12 - 15 M_{\odot}$)

$E_{\text{exp}} = 8 \times 10^{50} \text{ erg}$ and $M_{\text{Ni}} = 0.063 M_{\odot}$ (Bersten+ 2012)

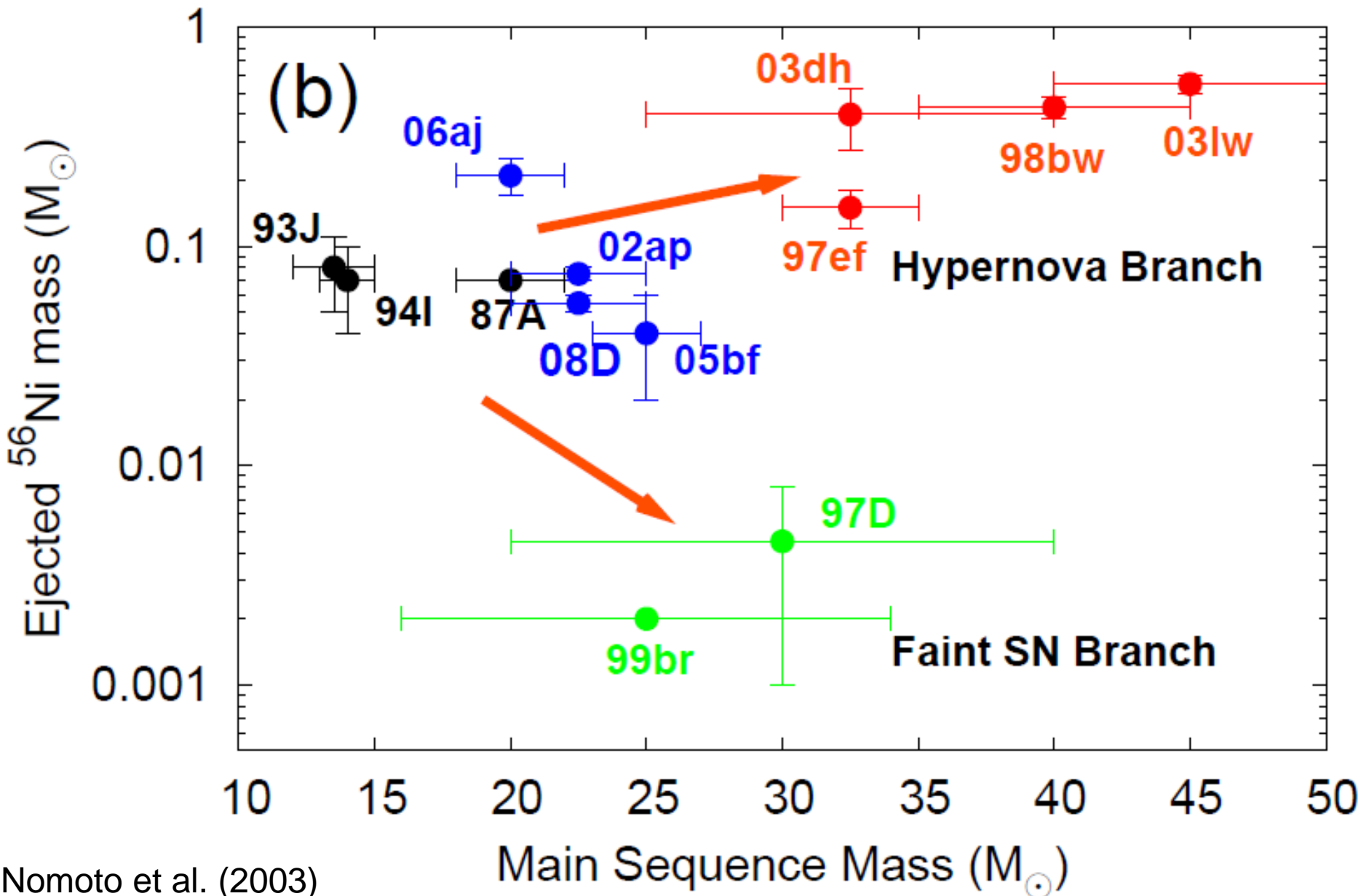
SN IIb 2011dh: Constraints on the Progenitor

- Models with He core mass of $\approx 4 M_{\odot}$ ($M_{\text{ZAMS}} \approx 15 M_{\odot}$), $E_{\text{exp}} \approx 8 \times 10^{50}$ erg and $M_{\text{Ni}} \approx 0.063 M_{\odot}$ reproduce very well the observations
- A large radius ($R \sim 200 R_{\odot}$), consistent with the pre-SN imaging, required to reproduce the early LC.
No contradiction with the temperature
- He core mass $\gtrsim 8 M_{\odot}$ ($M_{\text{ZAMS}} \gtrsim 25 M_{\odot}$) ruled out \implies single star evolution unlikely
- Binary models give right position on HR diagram, and mass of H for a SN IIb \implies YSG may be the progenitor

SNe [M_{ms} -E relation]



SNe [$M_{\text{ms}} - M(^{56}\text{Ni})$ relation]

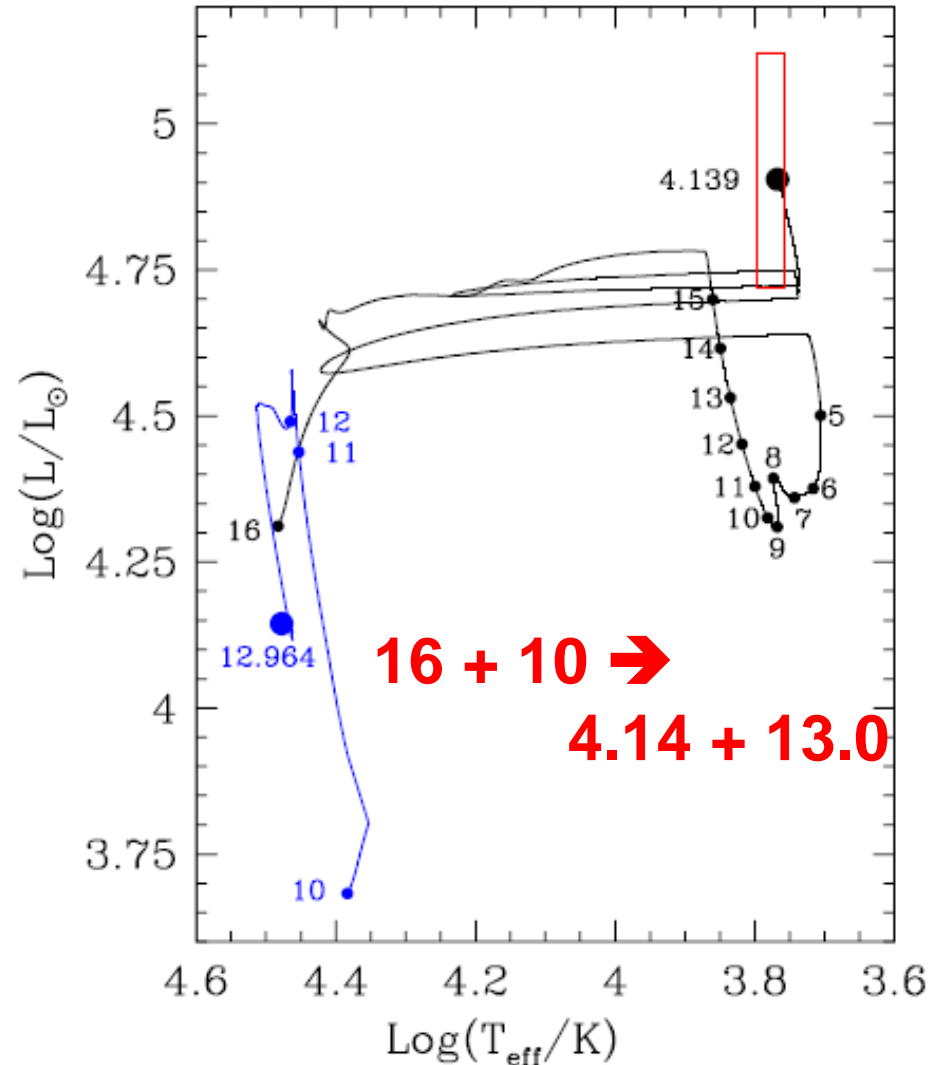
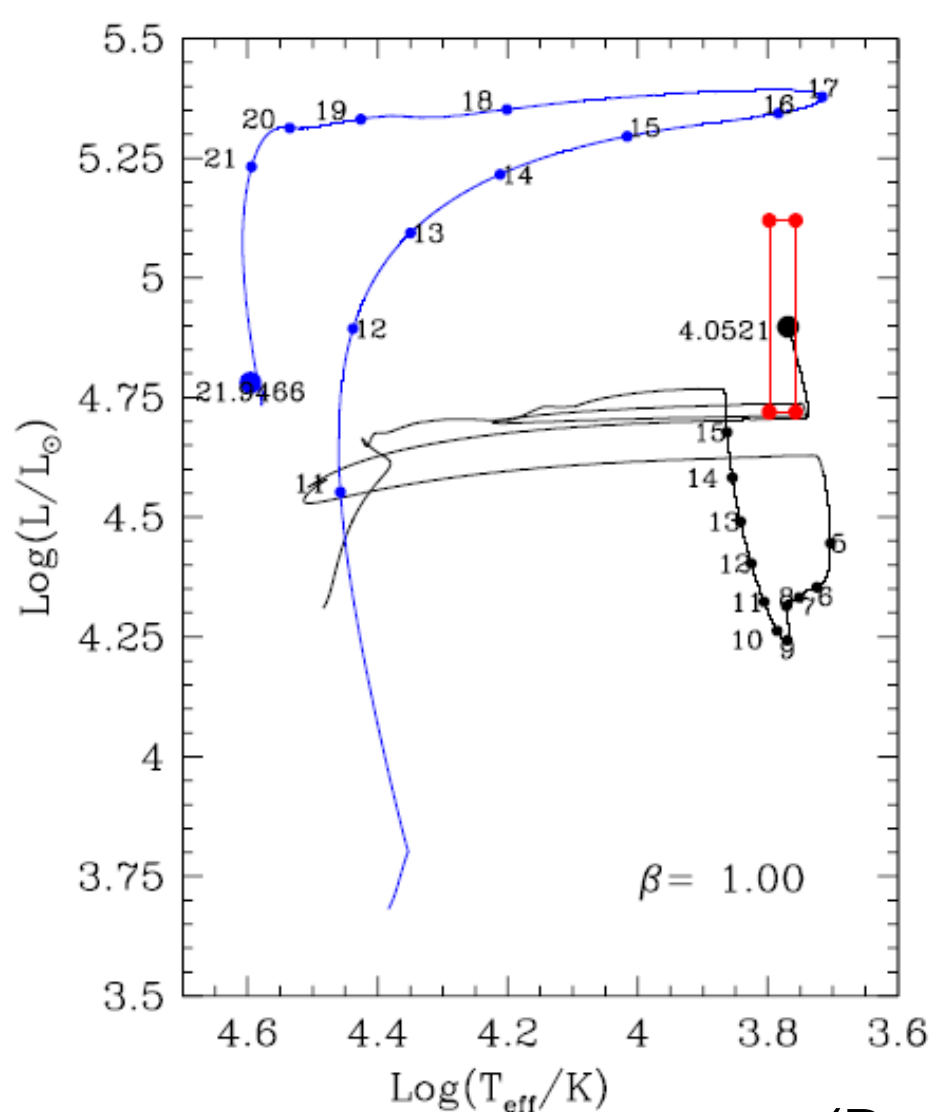


Close Binary Evolution

- $16 M_{\odot} + 10 M_{\odot}$
 - $P_0 = 125$ days
 - $\dot{M}_2 = -\beta \dot{M}_1$
-
- $4.14 M_{\odot} + 13 M_{\odot}$

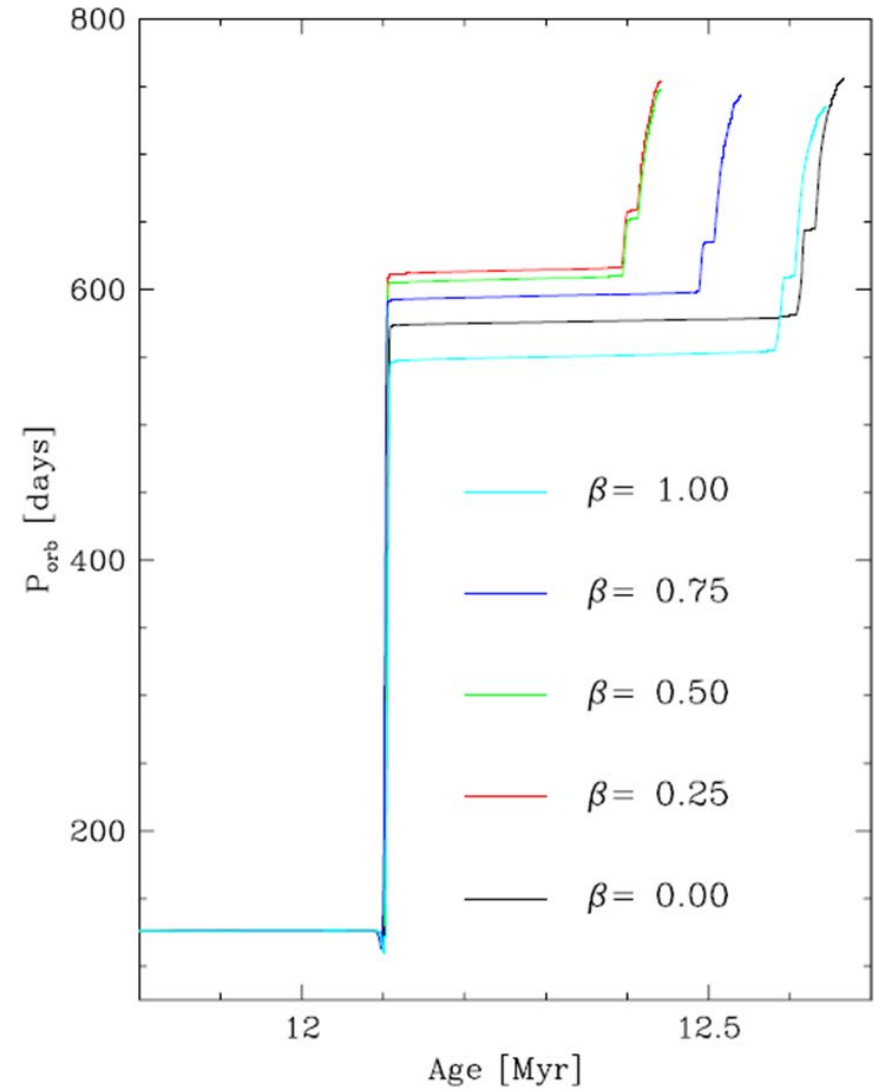
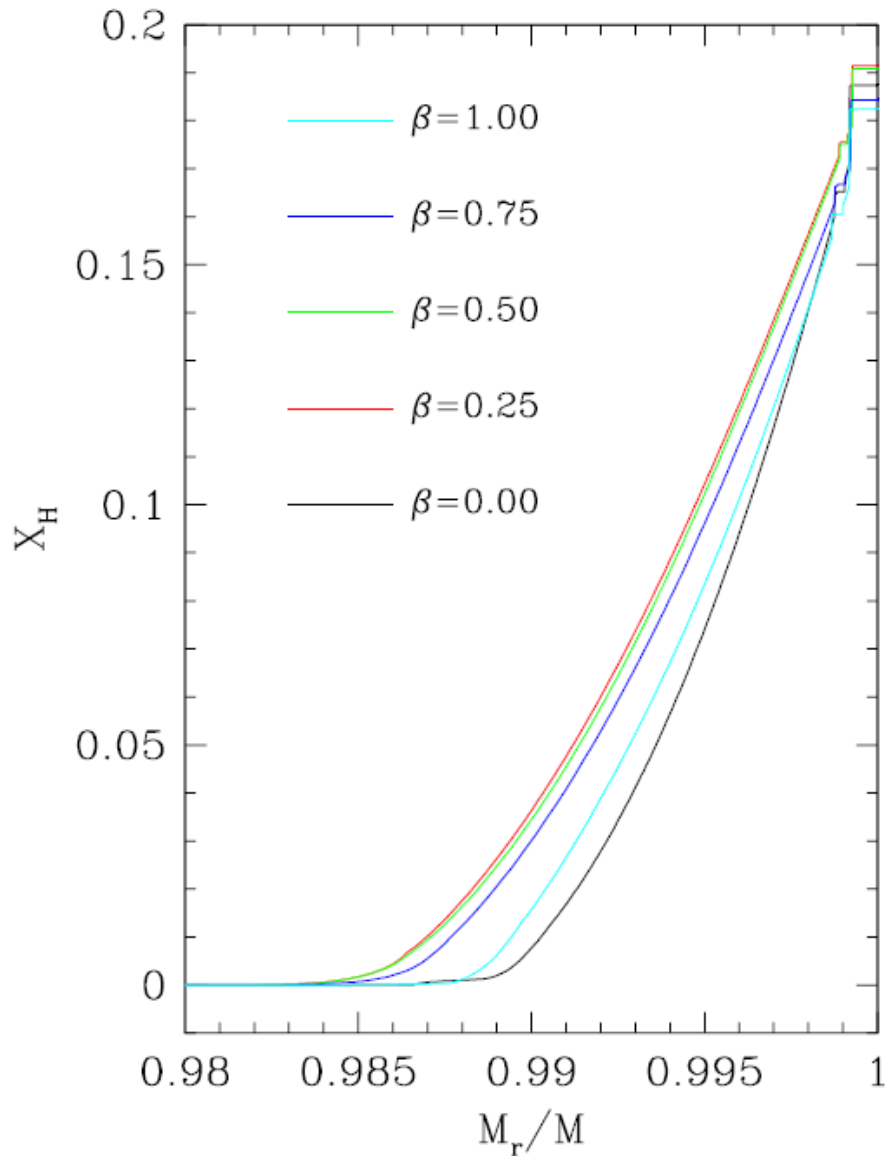
(Benvenuto+ 2012)

SN IIb 2011dh: Binary Evolution



(Benvenuto+ 2012)

Close Binary Evolution



(Benvenuto+ 2012)

Binary stellar evolution for SN 2011dh

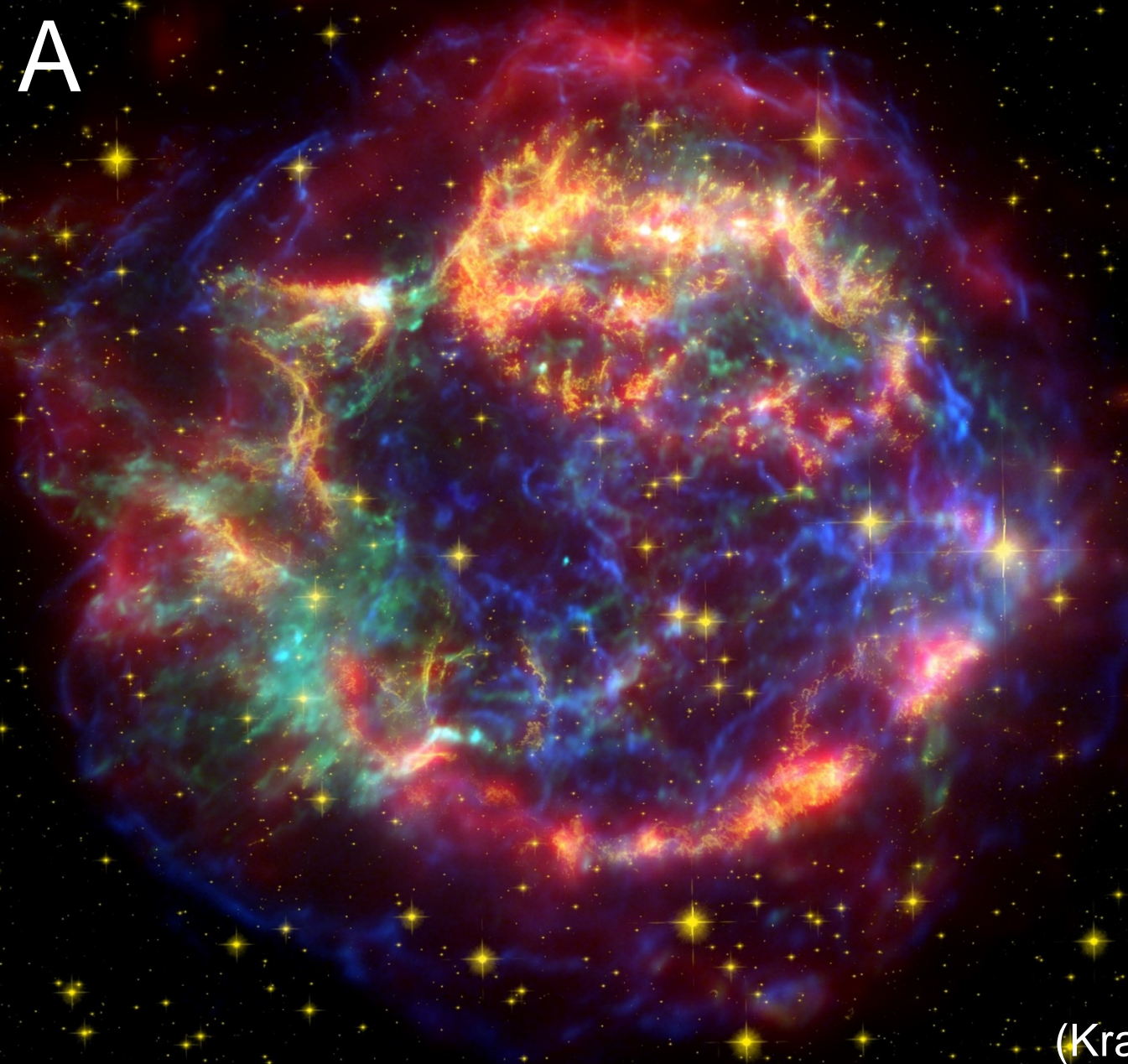
- Primary star of $16 M_{\odot}$ and period of 100 days
- Secondary star of $10 - 14 M_{\odot}$
- Conservative and non-conservative mass accretion



- Primary ends as **YSG** with He core mass of $\approx 4 M_{\odot}$ and H mass of $\approx 5 \times 10^{-3} M_{\odot}$

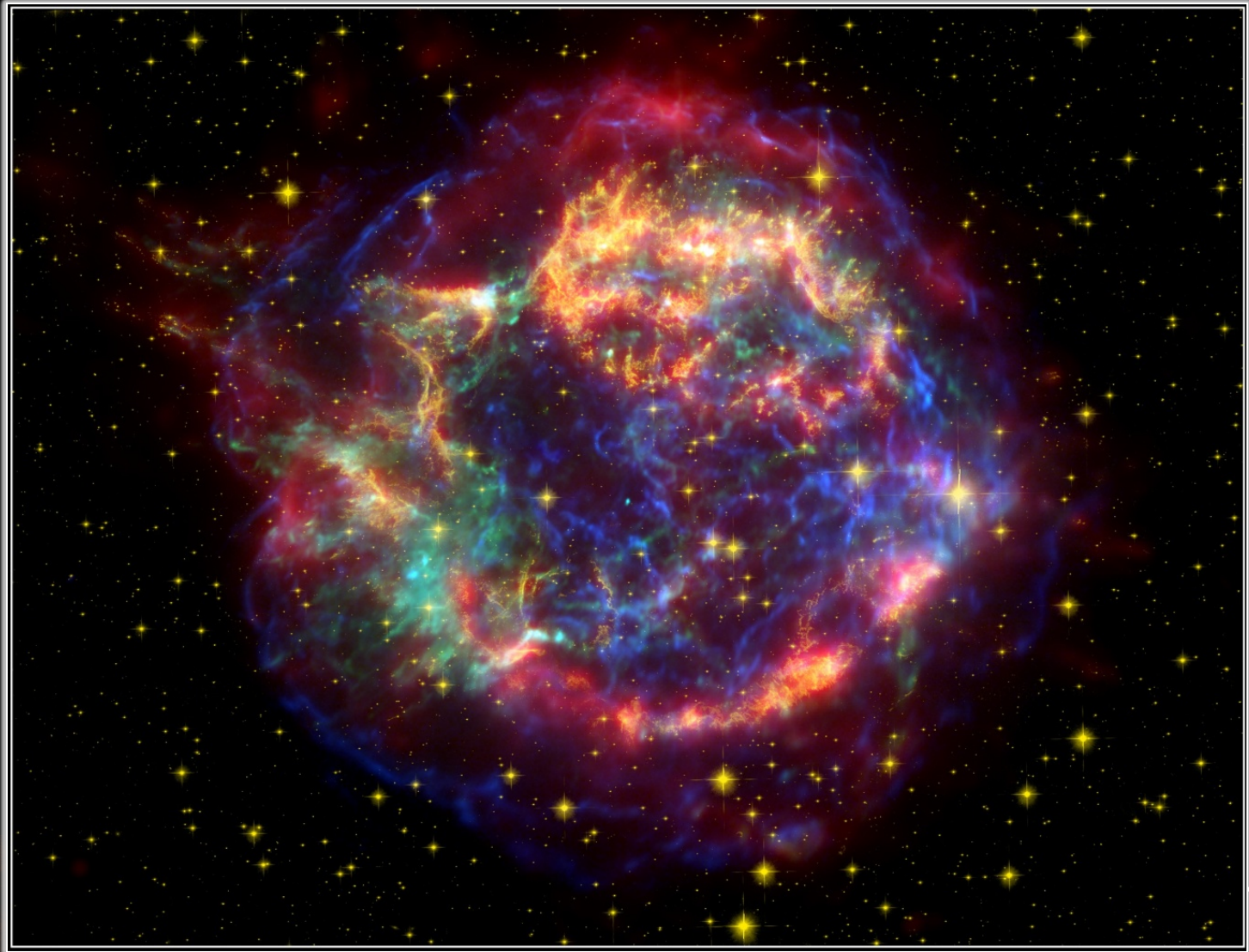
(Benvenuto+ 2012)

Cas A

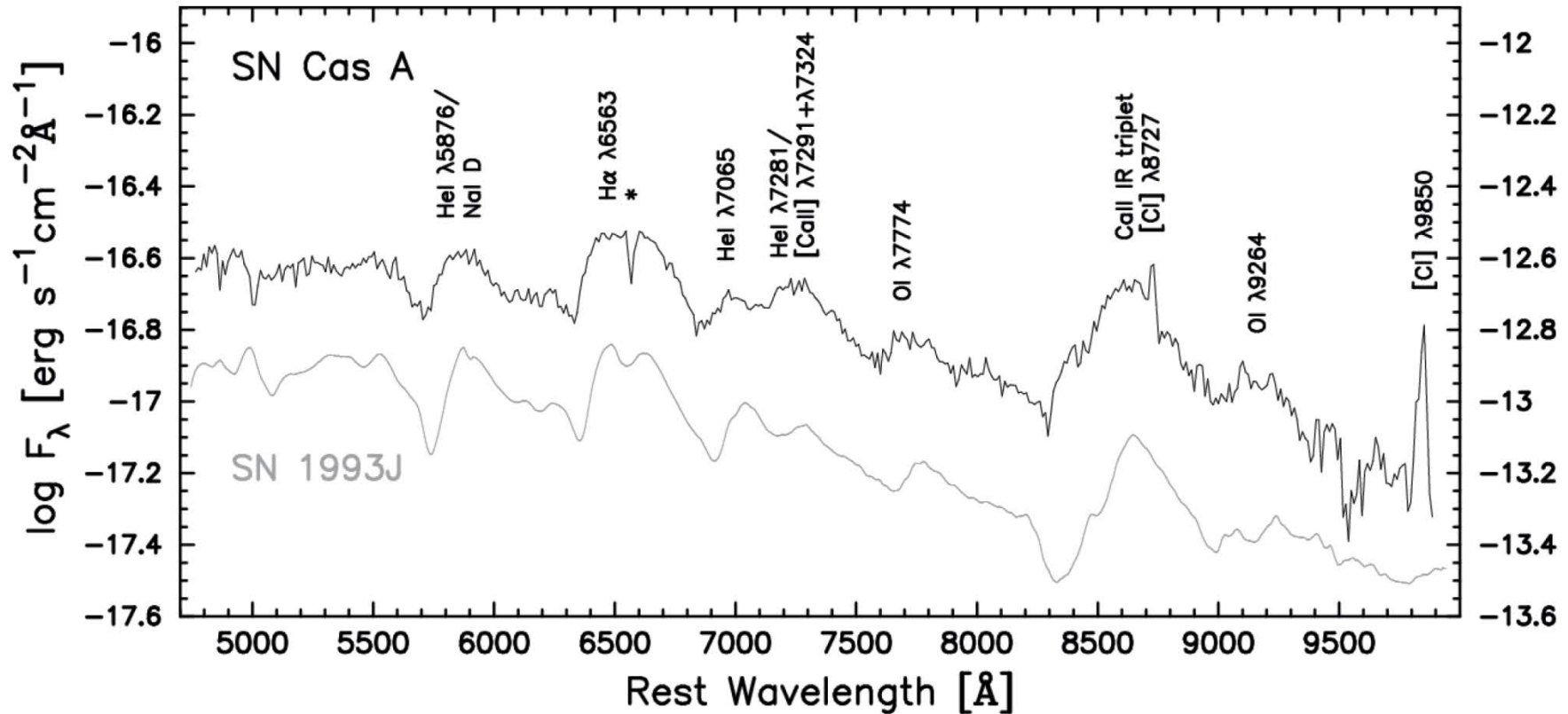


(Krause+08)

Light Echo from Cas A



Cas A: First spectrum of a Galactic SN

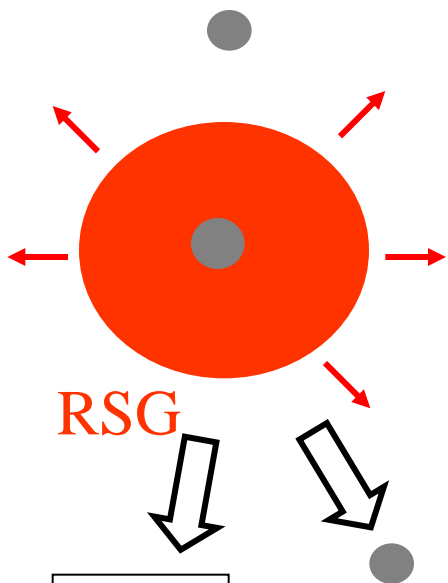


Krause et al., 2008, Science 320, 1195

SUBARU/FOCAS
5.5 h integration

SNe in Binary Systems

Single

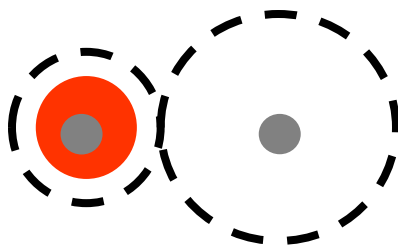
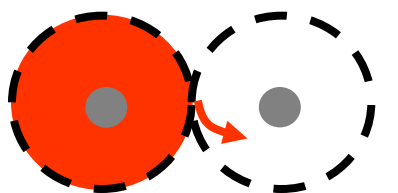


SNIi

Wolf Rayet
(WN, WC)

$M_1 \sim M_2$
"Conservative"

1 ● ● 2

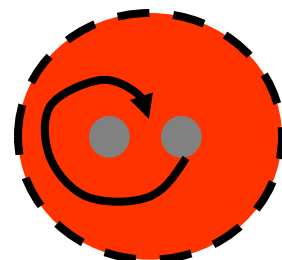
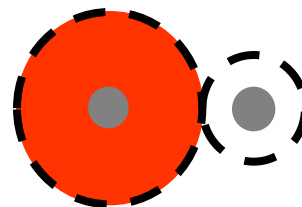


He, C+O Star

SNIb/c

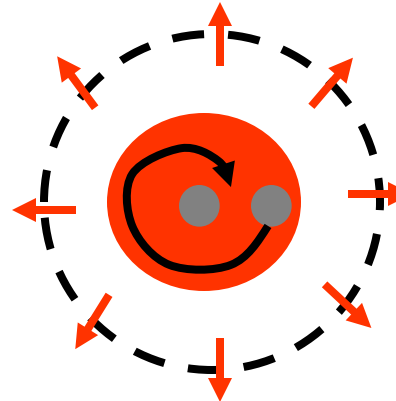
$M_1 \gg M_2$
"Non-Conservative"

1 ● ● 2



Spiral-in

Rapid Rotator



SNIb/c

?

Hypernovae?

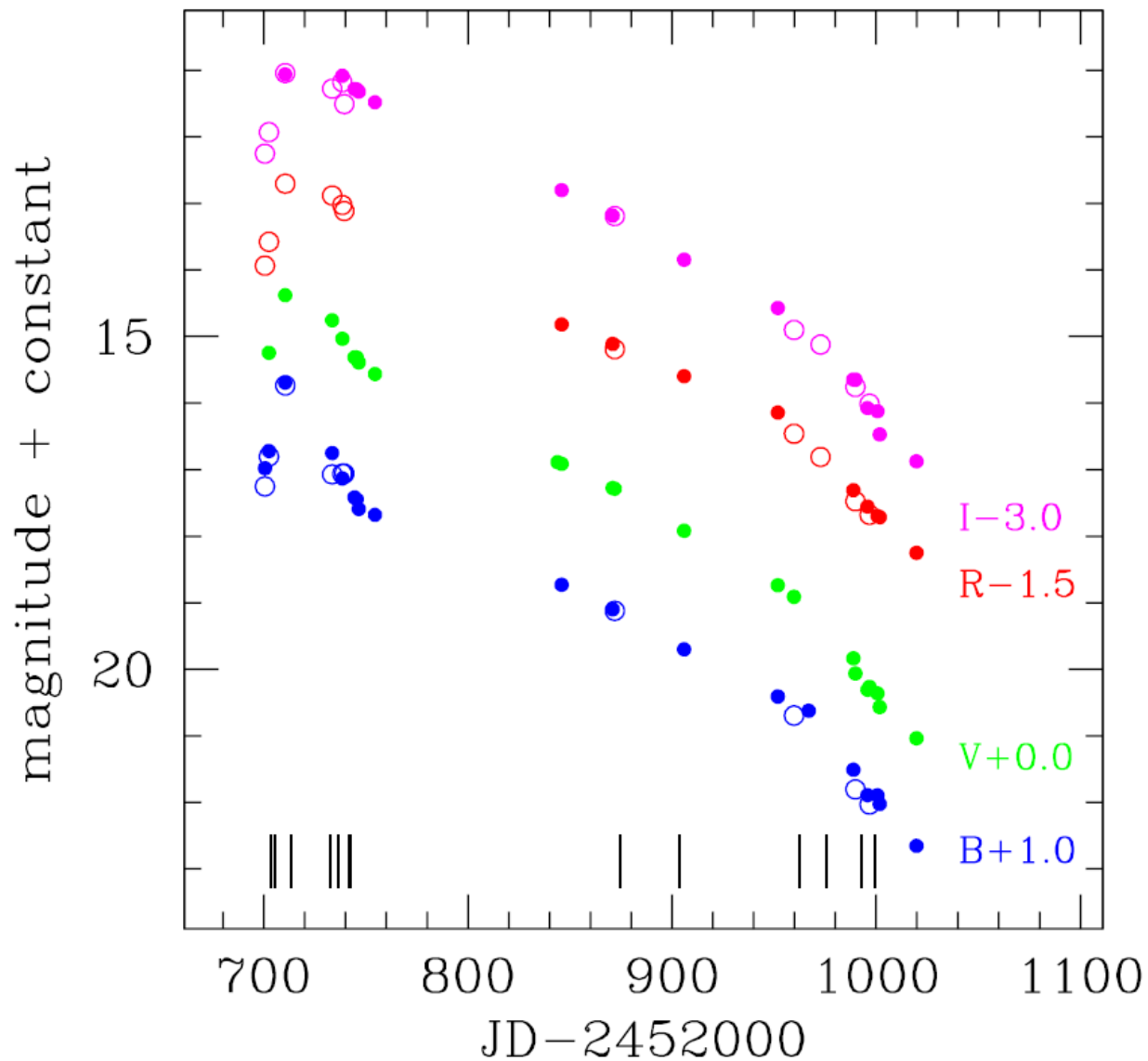
Binary's Final Fates

Massive Companion \rightarrow SN IIb \rightarrow
NS + Companion Star ($> 10 M_{\odot}$)

Spiral-In of a Small Mass Companion \rightarrow
Large Angular Momentum &
Enhanced Mass Loss \rightarrow Small $M(H)$ \rightarrow
SN IIb \rightarrow NS + No Companion : Cas A ?

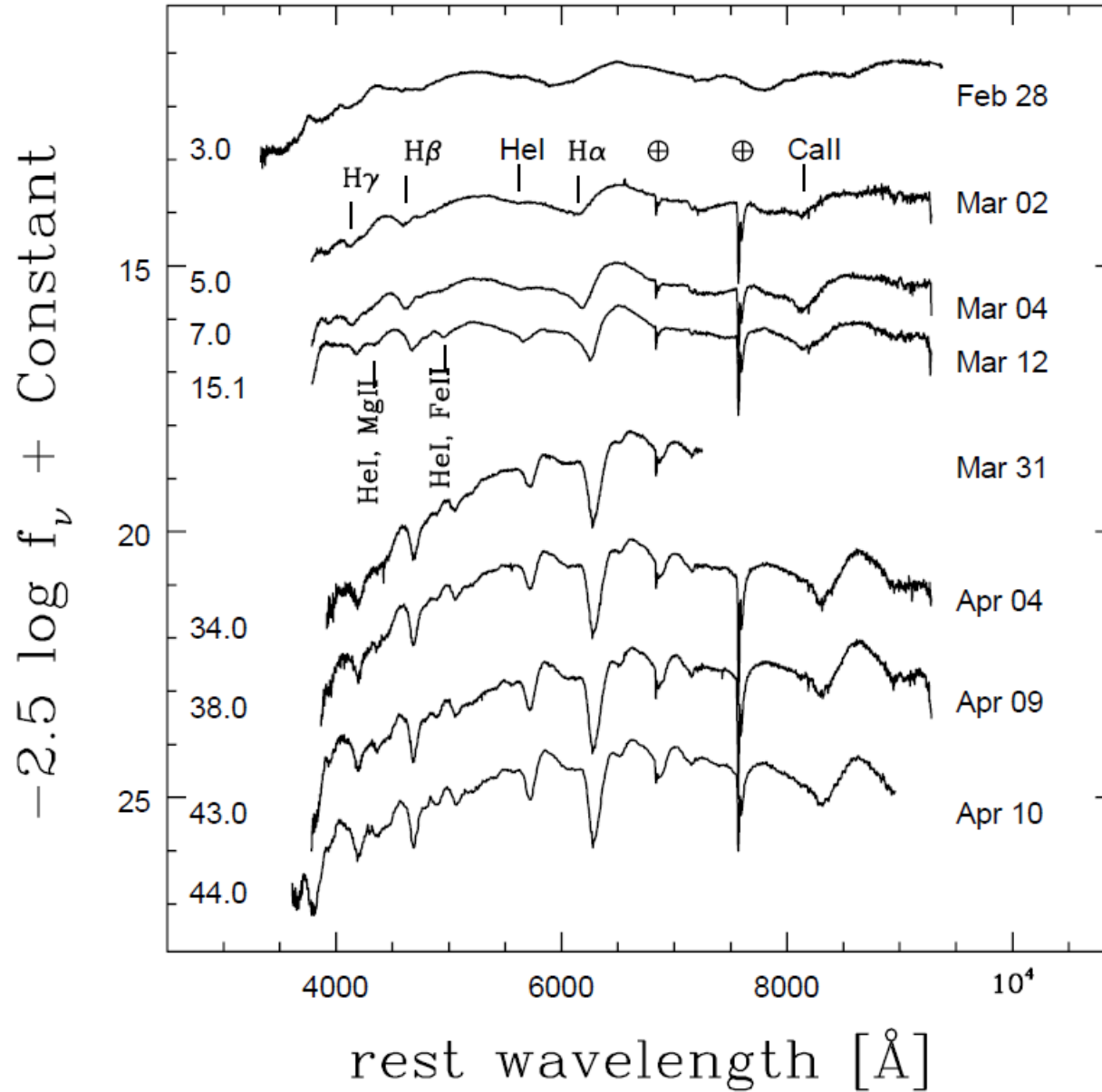
$M_1 > 25 M_{\odot}$ \rightarrow Spiral-In \rightarrow BH (rotating) \rightarrow
SN IIb : Hypernova ? (SN 2003bg?)

SN I Ib 2003bg

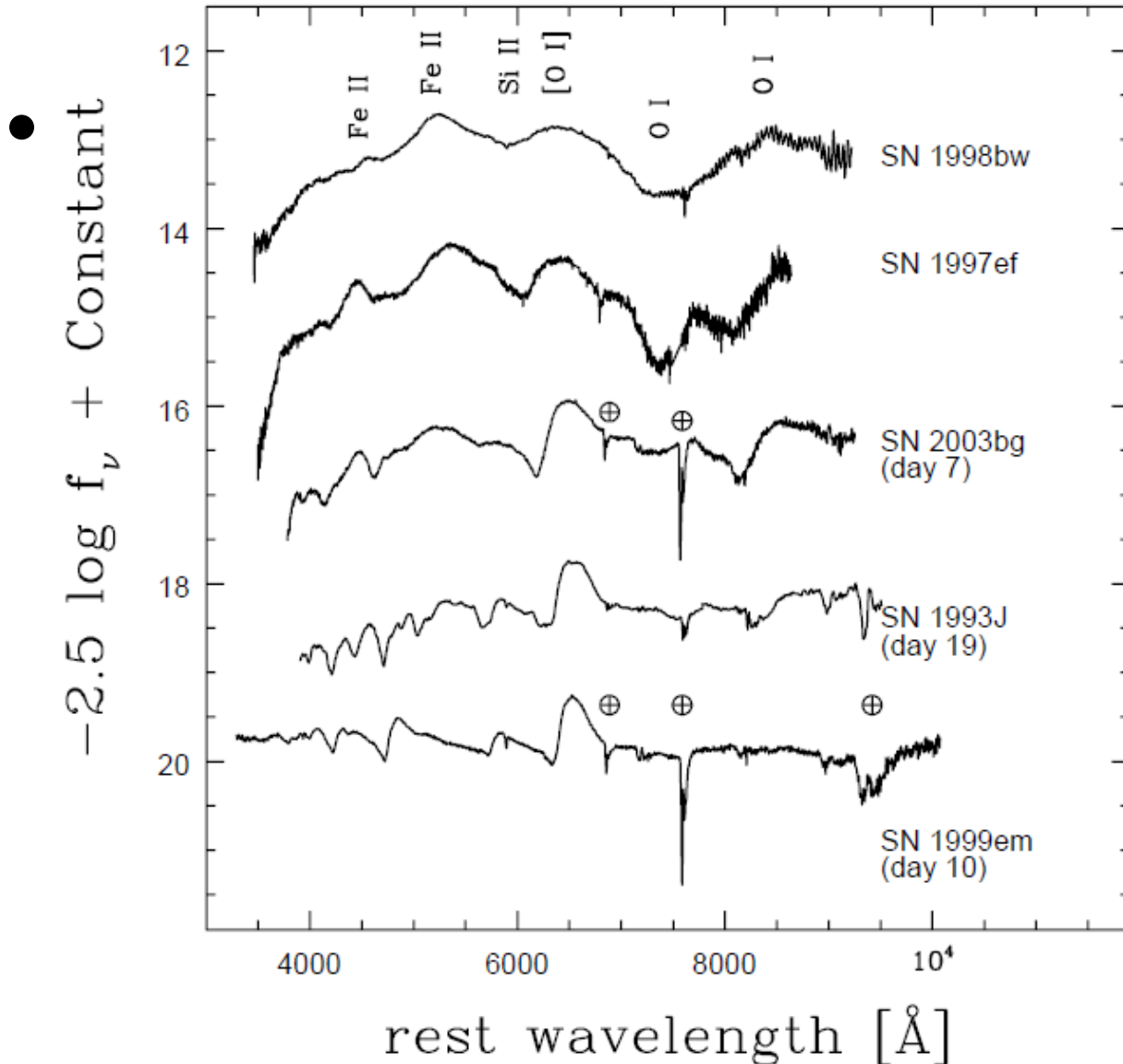


Hamuy+09

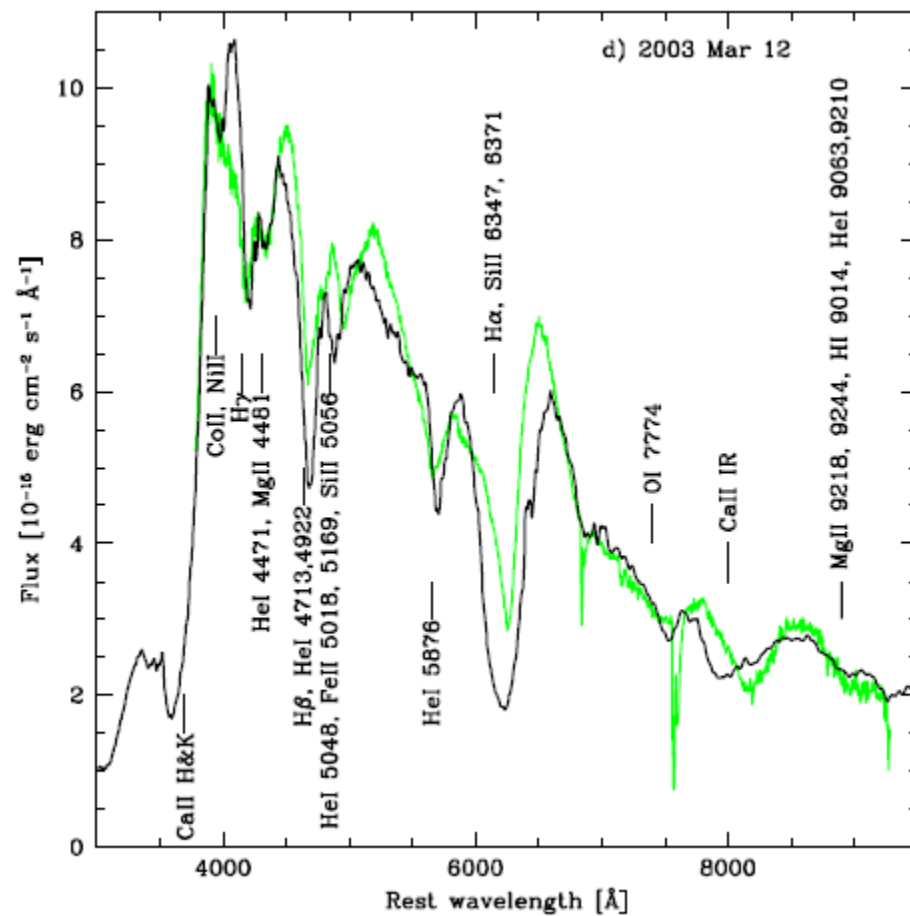
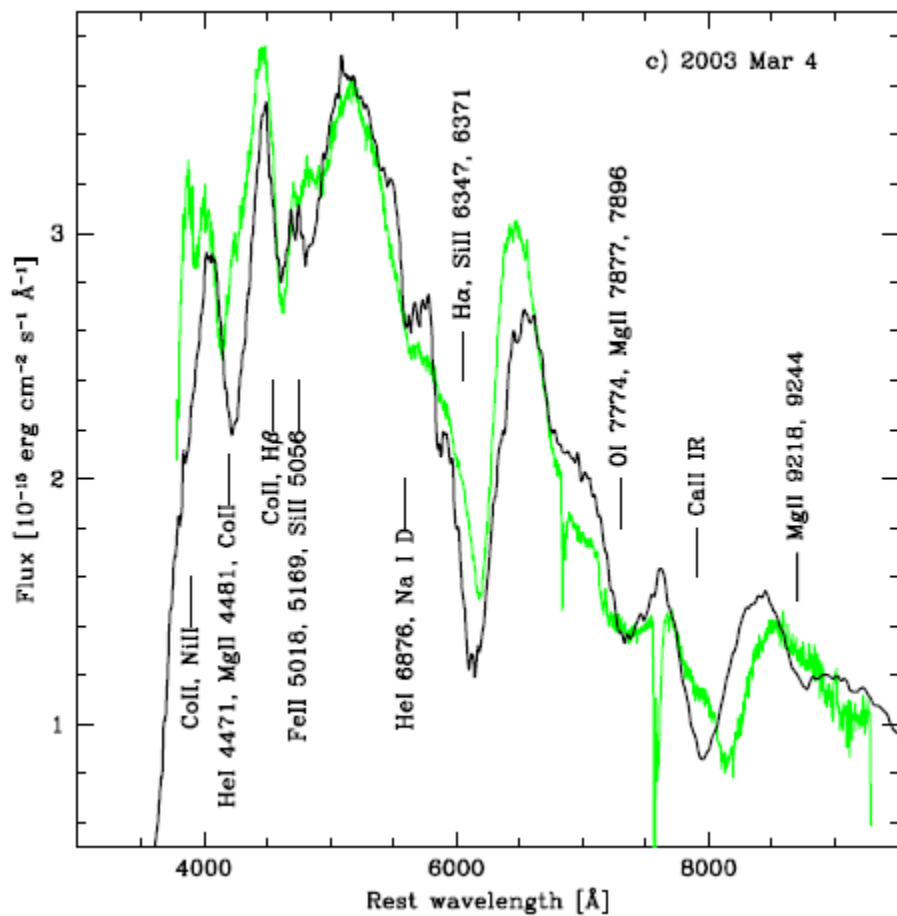
SN I Ib 2003bg



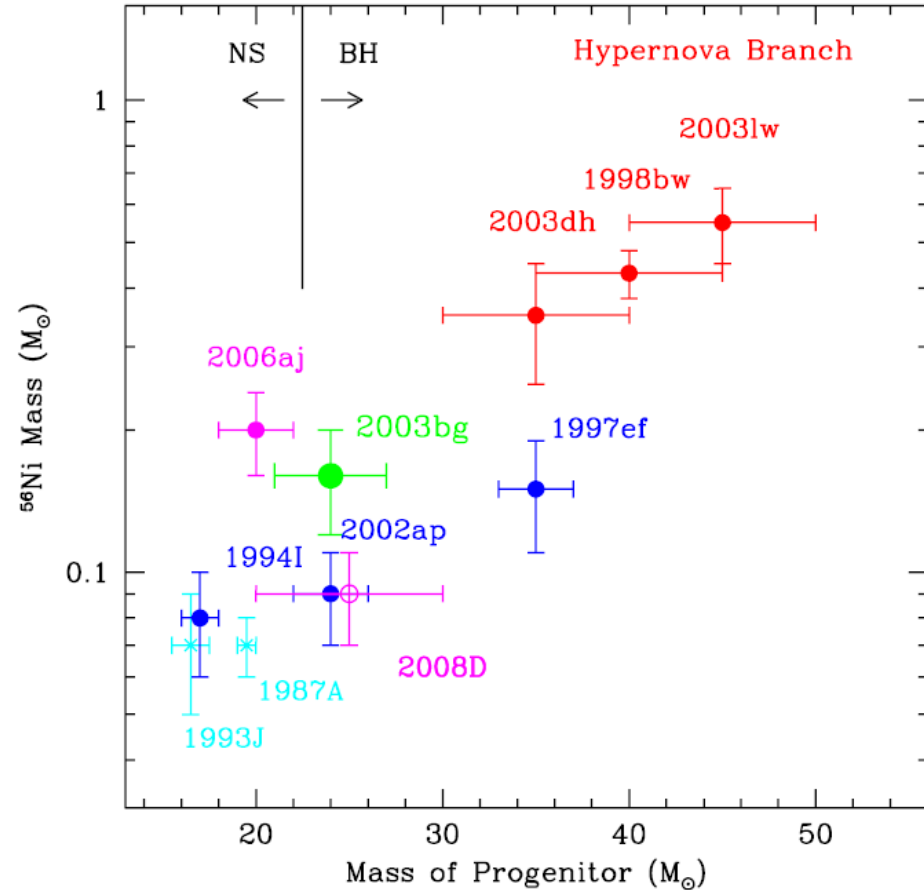
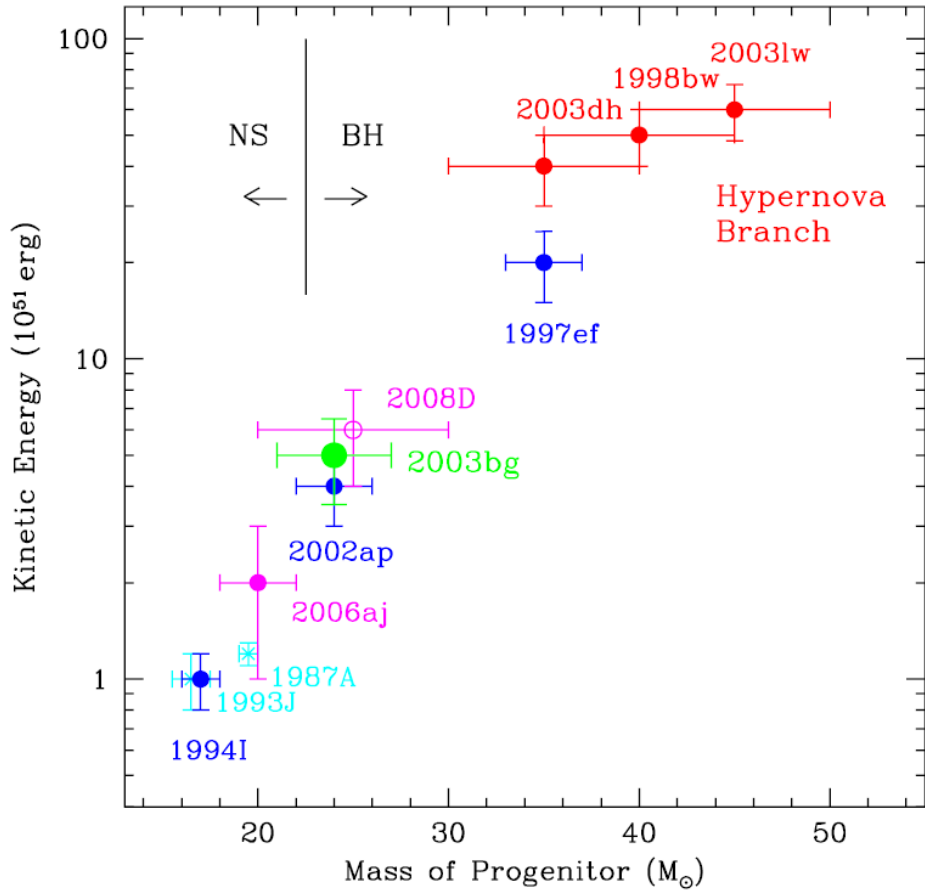
SN IIb 2003bg vs. Hypernova



SN Iib 2003bg



SN IIb 2003bg (E, ^{56}Ni)



$E \sim 5e51$ erg

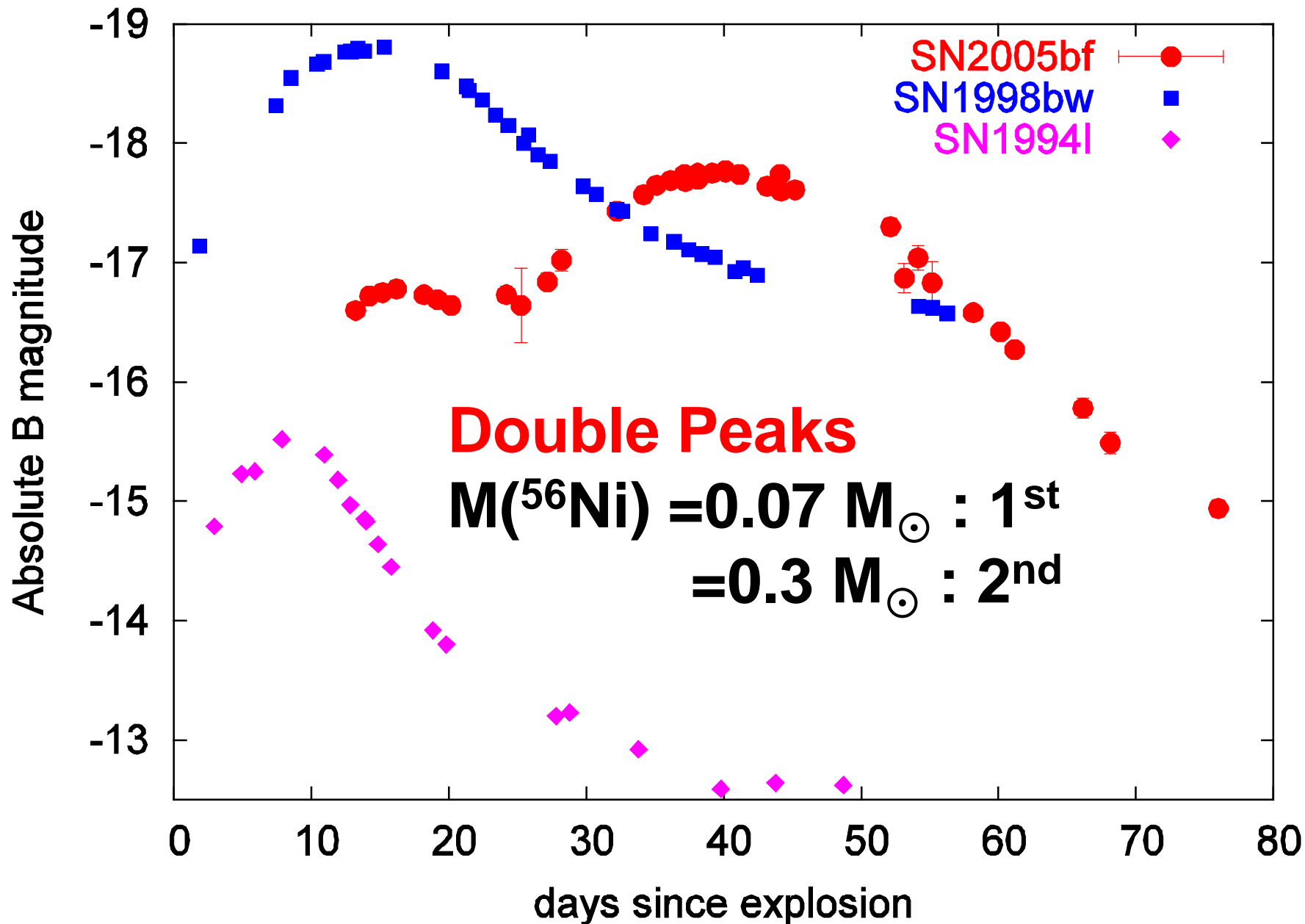
(Mazzali et al. 2009)

SN Ib 2005bf

Anupama et al. (2005)

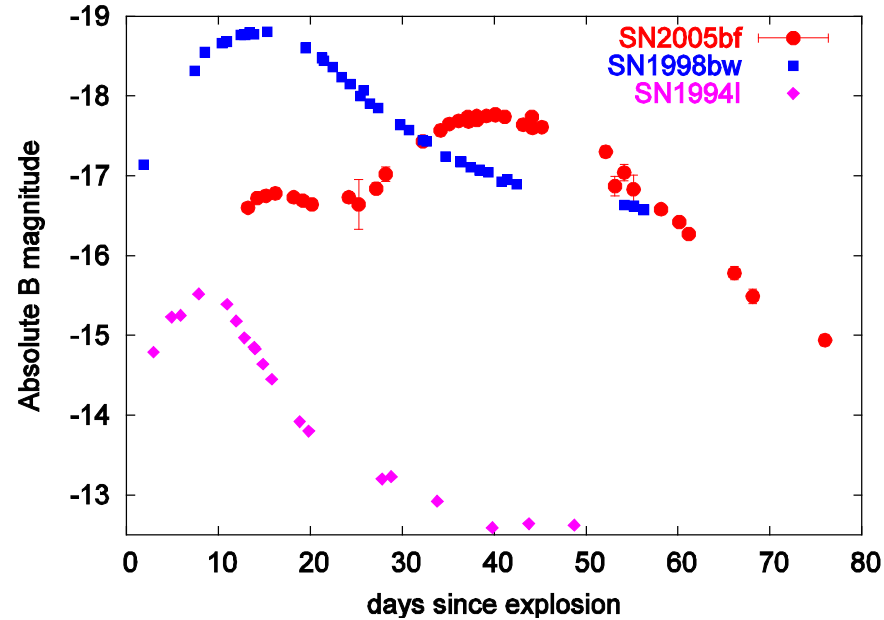
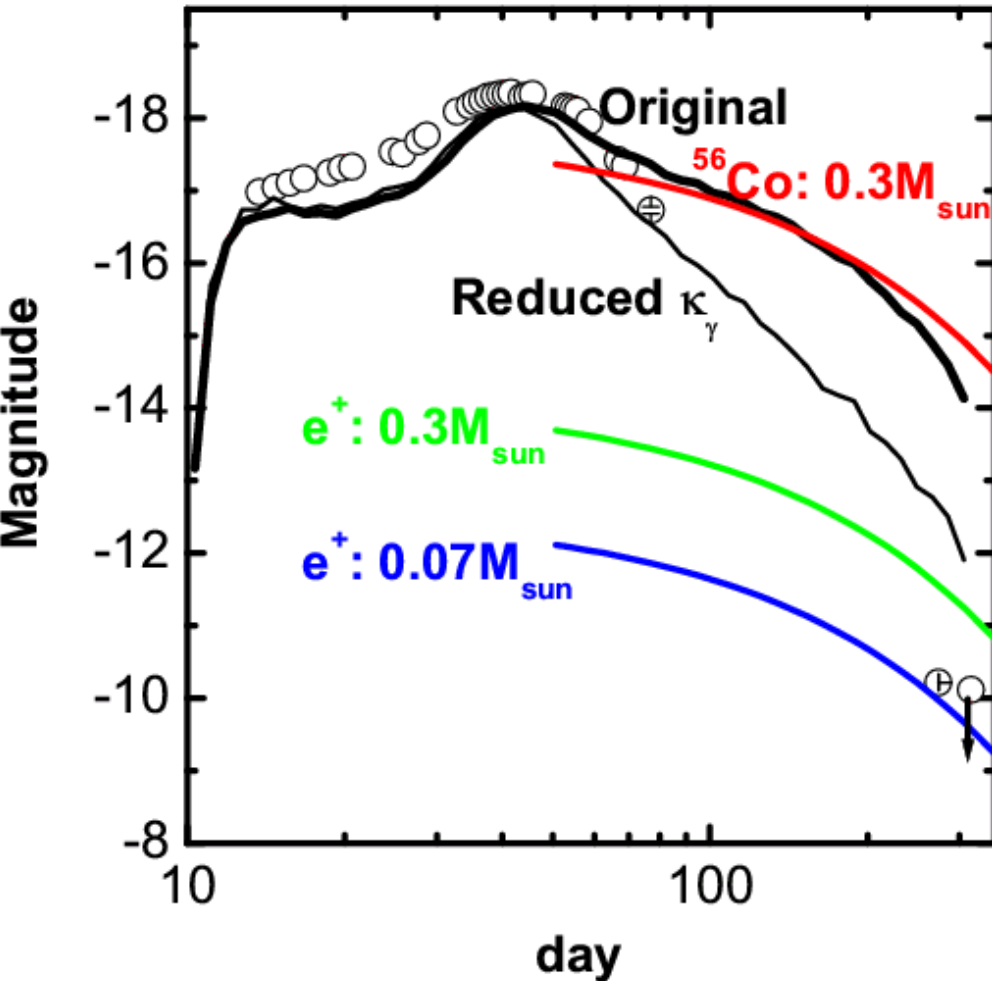
Tominaga et al. (2005)

Folatelli et al. (2006)



Magnetar ??

SN Ib 2005bf: Double Peak Light Curve

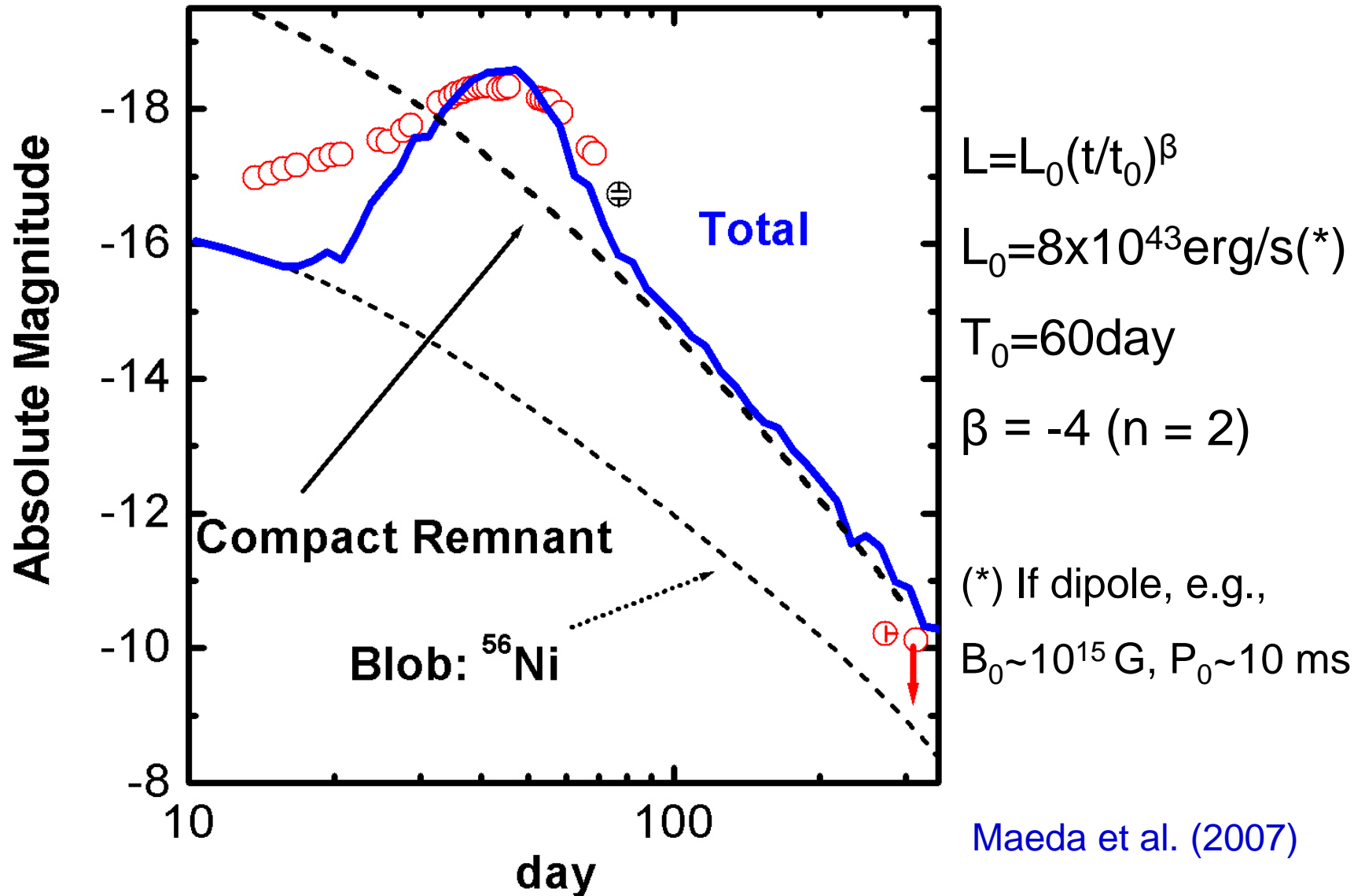


SUBARU obs

$M(^{56}\text{Ni}) < 0.07 M_{\odot}$

Maeda et al. (2007)

1st peak: ^{56}Ni decay
2nd peak: Magneter ??



Light Curve Models

Energy source

shock heating → II-P

radioactive decays

pulsar

circumstellar interaction

Progenitor's radius

single star vs. binary

companion star

Binary merger → single star → IIb, II-L, IIc

SNe in Binaries

- Spiral-In → Single star (+ heating)
- Enhanced Mass Loss
- **II-n II-L II-b**

(Nomoto+ 1995)

Binary's Final Fates

Massive Companion \rightarrow SN IIb \rightarrow
NS + Companion Star ($> 10 M_{\odot}$)

Spiral-In of a Small Mass Companion \rightarrow
Large Angular Momentum &
Enhanced Mass Loss \rightarrow Small $M(H)$ \rightarrow
SN IIb \rightarrow NS + No Companion : Cas A ?

$M_1 > 25 M_{\odot}$ \rightarrow Spiral-In \rightarrow BH (rotating) \rightarrow
SN IIb : Hypernova ? (SN 2003bg?)